SCHOOL OF
CIVIL ENGINEERING

INDIANA
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JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-89/17

Final Report

AN EVALUATION OF LEADING VERSUS LAGGING LEFT TURN SIGNAL PHASING

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Robert E. Montgomery
Kumares C. Sinha

PURDUE UNIVERSITY

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TO: Harold L. Michael, Director
Joint Highway Research Project

December 13, 1989

Project: C-36-17QQ

FROM: Kumares C. Sinha, Research Engineer
Joint Highway Research Project

File: 8-4-43

Attached is the Final Report on the first part of the HPR Part II Study, "An Evaluation of Leading Versus Lagging Left Turn Signal Phasing and All Red Clearance Intervals." This report presents the research findings on leading vs. lagging left turn signal phasing. A set of guidelines for the use of leading and lagging left turn signal sequences is also included. The research for this report was conducted by Joseph E. Hummer under the direction of me and Prof. Robert E. Montgomery.

This report is forwarded for review, comment and acceptance by the INDOT and FHWA as partial fulfillment of the objectives of the project.

Respectfully submitted,

KCSinha

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Research Engineer

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An Evaluation of Leading Versus Lagging Left Turn Signal Phasing

Final Report

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16. Abstract

This research project includes an evaluation of leading vs. lagging left turn signal phasing and all red clearance intervals. This report presents the results of the part of the research involving leading vs. lagging left turn signal sequences. It was found that, in general, lagging sequences at selected types of intersections can provide safety and delay advantages over the (more common in Indiana) leading sequences. Guidelines were developed on the basis of research results for the use of the leading and lagging signal sequences in Indiana.

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CHAPTER 1 - INTRODUCTION

General

Left turns at intersections have long been a source of concern for traffic engineers. In recent years, greater traffic volumes at many intersections and fiscal and right-of-way constraints on construction have led traffic engineers to design and implement increasingly more sophisticated signal schemes to allow vehicles to turn left safely and efficiently. The most common type of signal scheme accommodating left turns in the United States remains the permissive scheme. In this scheme vehicles may turn left when receiving the green ball signal and when sufficient gaps appear in the opposing traffic stream which also has a green ball signal. In another very common signal scheme, the protected scheme, vehicles may turn left only when receiving a green arrow signal which affords them exclusive right-of-way through the intersection. In most applications, the protected signal is given to vehicles turning left from a particular street before the green ball is given to the through movement on the same street (i.e., protected-leading). Most other common signal schemes to accommodate left turning vehicles involve a variation on or combination of permissive and protected schemes, including:

- protected-lagging, by which the green arrow is given to left turning vehicles after the through movements have been serviced,

- protected-permissive, by which protected left turns are made first in the cycle and a green ball signal allows permissive left turns later in the cycle, and

- permissive-protected, by which permissive left turns are allowed first in the cycle and protected left turns are accommodated later in the cycle.

Protected-leading and protected-permissive are collectively referred to as "leading" schemes, while protected-lagging and permissive-protected are known as "lagging" schemes.

Research has been conducted on a number of questions about the common left turn schemes. However, the question of the effects of leading and lagging schemes has received little attention from researchers. Many localities and practitioners, faced with the choice of lead or lag, base their decision on tradition, hearsay, or feeling without any factual evidences. The intent of the present research was to examine the relative merits of leading and lagging phasing schemes and to develop appropriate guidelines that would assist decisions on lead and lag.

There are large potential benefits from an answer to the leading and lagging sequence question. If the guidelines mean one less second of delay per vehicle at 200 typical intersections, about one million hours per year will have been saved. Large fuel and pollution savings would also result from such a reduction in vehicle delay. Additional benefits could accrue to INDOT and to taxpayers if construction projects to add capacity at intersections are delayed or scaled down because of the changes in signal sequence. Also, while the number of accidents involving left turning vehicles per intersection is relatively small (see Chapter 5), there is the potential for the guidelines to result in accident savings as well.

Purpose and Scope

The primary purpose of the research described herein was to produce guidelines for the use of leading and lagging left turn signal sequences, as discussed above. A secondary purpose of the research was to advance the body of knowledge regarding left turn signal schemes in general. For example, the simulation studies conducted in this research (Chapter 6) revealed that permissive signals, which are usually more efficient than the permissive-protected signals in terms of delay, were actually less efficient when the progression band along the major street made most vehicles arrive at the intersection during the red signal phase. Information of this nature would be useful in compiling a comprehensive set of guidelines on left turn phases.

The scope of the research was limited in a number of ways. First, attention was given primarily to only the five common left turn schemes described above. Second, data collection activities were confined to Indiana to avoid geographical bias. Third, with one exception the research was concentrated on intersection types which are relatively common in Indiana. Intersections with five or more approaches, dual left turn lanes, offset approaches, or a great deal of channelization are rare in Indiana, so the limited resources of the project were not expended on them. Although they are not common in Indiana, diamond interchanges where both ramp terminals had signals with left turn arrows were included for study because an increasing number of the interchanges is being signalized.

Report Outline

The major areas of potential concern relative to leading and lagging and other left turn issues which were explored in this research include motorist

preferences and understanding, safety, and delay. All of these areas are addressed in Chapter 2, which contains a summary of relevant past published research findings. Data on motorist preferences and understanding were gathered using a survey at the 1988 Indiana State Fair, the results of which are presented and analyzed in Chapter 3. Safety was explored using a field study of traffic conflicts (Chapter 4) and an analysis of accident data at a sample of intersections (Chapter 5). A detailed microscopic simulation model of arterial street networks was the primary tool used to study delay. A discussion of the simulation model, experiment set-up, and results is presented in Chapter 6. Safety-related variables were also analyzed using a series of simulation runs, and those data are also presented in Chapter 6. The guidelines on leading and lagging sequences and a summary of other research findings comprise Chapter 7.

CHAPTER 2 - LITERATURE REVIEW

Introduction

A summary of the literature review on leading and lagging signal sequences is presented in this chapter. The literature relating leading and lagging to delay is presented first, followed by safety and then other aspects of the leading and lagging issue. Also included in this chapter is a brief review of past research on other left turn signal issues. The literature review served several purposes during the study, such as identification of aspects of the issue which have and have not been adequately answered and identification of factors which may interact with the choice of leading or lagging sequence.

Delay

Isolated Intersections

Several claims for the better performance of lagging over leading sequences in terms of delay at isolated intersections are made in the literature. Hawkins [1963] composed a list of the possible advantages of the lagging sequence, and he stated that, "Less time (is) needed for the lag since left turns can filter through (on) the straight through indications." However, Hawkins did not provide any supporting data and did not eloborate on his claim. Also, the advantage cited by him does not hold for protected-lagging signals. Engineers in Tucson, Arizona [City of Tucson undated] made a similar claim and supported it with facts. In changing several arterials from protected-permissive to permissive-protected, the City of Tucson was able to reduce the signal cycle length by ten percent, which led to reduced delay on

the order of 15 to 20 percent. Another conversion from protected-permissive to permissive-protected in Scottsdale, Arizona yielded similar results, with the lagging arrow at actuated signals requiring from two to eight percent less of the signal cycle than the leading arrow had at the same locations [Basha 1988a].

A claim was also made for lagging sequences at isolated intersections that since more vehicles are typically waiting to travel straight than turn left, providing the green ball for through traffic earlier in the cycle will be beneficial [Basha 1988b]. However, the claim was unsupported and remains highly dependent on the relative turning and through volumes.

Leading sequences at isolated intersections with four approaches are said to enjoy an advantage because of the capability for overlapped phasing (i.e., eight phase operation when all four approaches have left turn phases) [Florida Section 1982]. Delay is minimized when the signal controller is able to shift the right-of-way from a left turn phase with no more vehicles being served to the opposing through phase with waiting vehicles. Overlapped phasing is not usually recommended for permissive-protected signals due to a safety problem called "trapping" (discussed later in the Chapter). Protected-lagging signals do not appear to have a problem with trapping, so the advantage enjoyed in overlapped phasing by leading sequences does not extend to protected-leading sequences.

Another advantage leading sequences offer is that they clear left turning vehicles out of an intersection approach earlier in the cycle [Hawkins 1963]. For approaches with inadequate or no left turn vehicle storage, this feature can allow relatively free movement of through traffic.

Past experimental results show that the different advantages associated with the leading or lagging sequence do not translate into a clear favorite in terms of delay at isolated intersections. An early simulation study of lead and lag at diamond interchanges showed that leading phases minimized delay, especially when traffic volumes were high and the volumes were much higher in one direction on the signalized arterial than the other [Munjal, et al. 1972]. A later simulation study of an isolated intersection with four approaches under a variety of traffic and other conditions led to the conclusion that protected-permissive sequences cause less delay than permissive-protected sequences with fixed-time signals but more delay with actuated signals [Machemehl and Mechler 1984]. No difference in delay was seen during the same study between protected-leading and protected-lagging sequences. The field studies conducted in Arizona mentioned previously [City of Tucson undated and Basha 1988a], of course, supported the idea that permissive-protected sequences caused less delay than protected-permissive sequences.

Intersections with Coordinated Signals

There is very nearly a consensus in the literature on the relationship of leading and lagging sequences to delay at intersections in coordinated signal control systems. It is claimed that relatively wide green-time through bands are possible in many coordinated systems if the choice of left turn sequence at particular approaches is not restricted [McKay 1966 and FHWA 1981]. Several studies have provided evidence to support this position, including Cohen and Mekemson [1985], who used the NETSIM simulation model to demonstrate that optimizing the through bands on a set of arterials by manipulating the left turn sequence reduced delay by up to 19 percent over other left turn sequence policies. Other researchers supported the conclusion by using the

TRANSYT simulation model to show that a policy allowing a leading sequence on one approach of an intersection and a lagging sequence on the opposite approach saves motorist time in a wide variety of coordinated systems over a policy allowing just leading sequences [Christopherson and Riddle 1979]. The delay savings in the conversions of arterials in Tucson, Arizona from leading to lagging were also partially attributed to better progression [City of Tucson undated].

The mention has also been made in the literature that the lagging sequence may lead to less delay in coordinated systems. Hawkins [1963] pointed out that actuated controllers which terminate a leading left turn phase early in favor of an opposing through phase may not be doing the through traffic any favors in a coordinated system because that traffic will then arrive at the next downstream signal early. Other engineers have also made the same point, and have added that in a coordinated system vehicles which arrive with the through band and want to turn left must wait almost a complete cycle before receiving a leading green arrow signal [Basha 1988b].

Safety

Trapping

Concern for the safety of drivers and passengers in vehicles which become "trapped" in an intersection while waiting to make a left turn has been consistent in the literature [Hawkins 1963, Basha 1988b, Florida Section 1982, and McKay 1966]. Trapping occurs to a vehicle making a left turn on an approach with a permissive signal where the opposite approach has a permissive-protected signal. When the permissive signal goes to yellow and then to red (in order to provide the lagging green arrow signal for the left

turning traffic in the opposite direction), the signal for opposing through traffic remains green. A vehicle turning left with the permissive signal will not be able to complete its turn at the end of the cycle like at a normal permissive intersection. At best, the vehicle will be able to back up to the stop bar. If other vehicles in the left turn queue have moved up behind it, the lead vehicle will not be able to back up to the stop bar and will be trapped in the middle of the intersection. At worst, the driver of the left turning vehicle will not recognize that the opposing traffic still has a green signal and will try to turn, expecting the opposing traffic to stop as usual. The apparent danger of trapping virtually mandates that any approach with a permissive-protected signal must be accompanied by a protected left turn phase (or prohibited left turns) on the opposite approach and that if the opposite approach has permissive-protected phasing the protected phases must start simultaneously. It should be noted that no data were found in the literature reviewed to support the argument given above. Some localities, in fact, have maintained signals for many years which meet the conditions given above for trapping with no apparent hazard.

Other Safety-Related Issues

There are several reasons lagging sequences might lead to fewer accidents than leading sequences at certain types of intersections. Hawkins [1963] provided four such reasons including:

- lagging sequences provide for vehicle and pedestrian separation as pedestrians cross the street onto which left turning vehicles will turn at the beginning of the green interval,

- lagging sequences accommodate left turns in a manner more like normal (i.e., permissive signal) driving behavior,

- vehicles which are turning left just as the protected phase ends in a leading sequence may pre-empt the right-of-way (i.e., steal time) from the opposing traffic receiving a green signal, and

- opposing traffic may false start in an attempt to move with a leading green phase.

Hawkins also pointed out that the protected-permissive signal has a relative safety advantage in reducing the number of potential left and opposing traffic conflicts, since more vehicles presumably turn on the green ball with permissive-protected signals. The conclusions drawn by Hawkins were not supported by factual data.

Data to evaluate the above safety-related assertions are rare, however. One study provided relative estimated left turn accident rates (no particular normalizing statistic was provided) as follows: permissive, 1.0; permissive-protected, 0.73; protected-permissive, 0.35; protected (presumably either leading or lagging), 0.10 [FHWA 1981]. However, the data collected to establish such rates were too few and unreliable to place much confidence in them. Accident data collected to evaluate the conversion of signals on several Tucson, Arizona arterials from protected-permissive to permissive-protected showed that total accidents per entering vehicle fell forty percent during a six-month "after" period when compared to a four-year "before" period [City of Tucson undated]. The reduction in accident rate in the entire city over the

same time periods was 11 percent. The reduction due to the change in left turn sequence may not have been all that significant, however, because a stepped-up traffic enforcement program was undertaken at the same time as the signal phasing change took place. Very preliminary data from the conversion of some signals in Scottsdale, Arizona from protected-permissive to permissive-protected also showed a reduction in accident rates attributed to the conversion [Basha 1988a].

Other Lead and Lag Effects

As part of the effort to evaluate the effects from the conversion of some signals from protected-permissive to permissive-protected, the City of Scottsdale, Arizona established a telephone number for motorists to call and make comments on the change. A summary of the responses received through the first ten weeks after the conversion showed that the motorists who called overwhelmingly (84 percent) approved of the change [Basha 1988a]. The results were reported with the comment that, "This measure is significant as typical voluntary response surveys tend to attract negative comments."

Motorist confusion at being faced with different left turn signal sequences in close proximitv has been addressed several times. A test coordinated signal system in Dallas, Texas some years ago which contained different left turn schemes was monitored closely but no noticeable motorist difficulty with the schemes could be identified [Messer, et al. 1973]. Engineers reviewing the conversion of some Tucson signals mentioned above were also concerned about motorist confusion. Confusion was a concern for the time period immediately after the signal sequence was changed. Confusion was also a concern after the conversion because surrounding the signals with the new permissive-

protected sequences were many protected-permissive signals [Traffic Engineering Division, undated]. The observation of motorists negotiating the signals with the new sequences led to conclusions that:

- commuters mastered the new sequence "very quickly--in less than a week,"

- less frequent users of a route required longer education periods, and

- drivers can be expected to master the lagging sequence faster if signals are installed initially with the lagging sequence.

Another report discussing the Tucson conversion stated that for 12 months the City had lagging left turn sequences while surrounding Pima County had leading left turn sequences on its signals with "minimal confusion" [Basha 1988a].

Other Left Turn Signal Issues

The phase sequence issue has not been the primary focus of research on left turn signals. Rather, most of the research on left turn signal phases has examined the trade-offs between the permissive signal, signals which include protected and permissive left turn phases, and signals which include only protected left turn phases. The major general findings of the previous research on those tradeoffs include:

- protected-permissive or permissive-protected signals increase total delay and decrease left turn delay

relative to permissive signals (for moderate volumes of left turn and through traffic) [Stonex and Upchurch 1987 and Nemeth and Mekemson 1983],

- protected schemes increase delay relative to protected-permissive or permissive-protected signals [Agent 1979a and Upchurch 1986],

- warrants for the installation of protected-permissive or permissive-protected signals in the place of permissive signals based on traffic volumes and/or delay are available [Nemeth and Mekemson 1983, Upchurch 1986, Rouphail 1986, Cottrell 1986, and Lin 1982],

- accidents, especially left turn accidents, increase with permissive signals relative to protected-permissive or permissive-protected signals [FHWA 1981, Upchurch 1986, and Warren 1985],

- accidents, especially left turn accidents, increase with protected-permissive or permissive-protected signals relative to protected schemes [Agent 1979a, Upchurch 1986, and Warren 1985],

- protected schemes are recommended where traffic opposing a left turn approaches at high speeds [Agent 1979a] and

- protected schemes are recommended where sight distances for left turning vehicles are restricted, the

number of lanes of opposing through traffic to cross is three or more, dual left turn lanes are employed, or the accident history of the intersection indicates a problem [Florida Section 1982].

There has also been discussion in the literature on the so-called directional separation left turn scheme, whereby opposing approaches are given the exclusive right-of-way in turn. Directional separation is recommended if opposing approaches are significantly offset, left turn volumes are extremely heavy relative to through volumes, or left turns are made from a lane shared with through traffic [Florida Section 1982].

Chapter Summary

The literature on left turn phasing, especially the left turn phase sequence, was reviewed in this chapter. No clear trend emerged for leading and lagging sequences and delay at isolated intersections. However, it was clear that a policy which allows the choice of lead or lag at individual approaches in a coordinated system with the aim of maximizing through band width decreases delay. Safety emerged as a major concern with permissive-protected signals where trapping is possible, but generally there were more theoretical reasons and more data which showed that lagging schemes may be safer at some types of intersections. The only study reviewed which examined motorist preferences for lead or lag showed a great deal of support for the lagging sequence. The sparse data available on the question of motorist confusion when facing a change in signal sequences or a variety of sequences in close proximity showed few such problems. Finally, the plentiful literature on the tradeoffs between permissive, protected, and either protected-permissive

or permissive-protected signals was reviewed, and the well-known general trend that accidents increase and delay decreases as the level of left turn protection decreases was documented.

CHAPTER 3 - MOTORIST SURVEY

Introduction

This chapter describes the survey of Indiana licensed drivers conducted as part of the overall research effort. The purpose of the survey was to determine the relative levels of understanding of and preferences for the various left turn alternatives under consideration.

Previous surveys have been conducted on the subject of left turn treatments [Basha 1988a, Agent 1979a, Perfater 1982, Plummer and King 1974, and Benioff and Rorabaugh 1980]. However, there were several reasons that a new survey would provide more worthwhile data for this study. First, the context of the previous surveys, including time and place, were significantly different from the present study in Indiana. Second, the respondents to previous surveys came from similar areas, had similar backgrounds, and/or were limited in number. Finally, data on preferences for different signal alternatives were sparse. Especially critical was the paucity of data on motorist preferences for leading or lagging left turn phases. Thus, a survey which overcame these limitations was desired for this study.

Methodology

A survey instrument was desired for this project which would overcome the limitations of previous surveys, would provide data relatively quickly, and would remain within project budgetary restrictions. After more traditional telephone and mail survey techniques had been explored and rejected because of the very complex non-verbal messages to be conveyed to respondents, a personal interview format was selected as appropriate for the survey. The 1988 Indiana

State Fair was selected as the time and place for the interviews. The State Fair provided a convenient forum where a large, diverse sample of drivers from all parts of the state could answer questions.

The script for the interviews was pilot tested and revised many times prior to the State Fair. The final script is shown in Figure 1 and the corresponding form used by interviewers to record responses is shown in Figure 2. A major area of emphasis during the survey was the understanding of different signal and sign arrangements for left turns (Question 2). Each respondent viewed eight sign and signal displays during Question 2 and was asked to choose the correct action from among four potential left turn actions. Table 1 shows the eight signal displays each subject viewed during Question 2; the four choices for actions which were presented with the displays; and the definitions for "correct" actions, close (conservative) errors (which were actions that would probably not have catastrophic consequences in traffic), and gross errors (actions which would likely result in catastrophe in traffic) from among the four choices for action for each display.

There were three sign conditions tested with each of the three protected signal displays and three sign conditions tested with each of the three protected-permissive signal displays, as shown in Figure 3. Thus, for the protected and the protected-permissive signals, one-third of the respondents viewed each type of sign condition during Question 2.

The other major area of emphasis in the survey was the preferences expressed by respondents for the left turn signal alternatives (Questions 4 through 7). Four pairs of signal alternatives (all had no signs) were offered to the respondents during this phase of the survey, including permissive

LEFT-TURN SIGNAL PROJECT
MOTORIST QUESTIONNAIRE SCRIPT

"Thank you for helping with our survey. First, we need to make sure you are eligible to take the survey."

"Are you a transportation engineer or technician?"

"Are you a licensed driver in Indiana?"

"Have you or any member of your immediate family taken our survey earlier?"

"You are eligible to take the survey. The purpose of the survey is to find out about the understanding of and preferences for left turn traffic signals. Your answers will remain confidential. You will receive ______ Midway ride coupons after completing the survey. The survey is not difficult and takes about ______ minutes to complete."

"Are you ready to begin?"

"Standard red, yellow, and green traffic signals at an intersection look like this (show 0). Are you familiar with traffic signals which look like this?"

Figure 1. Survey script.

1\. a. "Are you familiar with traffic signals which look like this (show 3 or 5, random order)?"

b. Repeat Question 1. a. for the other (3 or 5) signal.

"Please read these statements about making left turns and tell me if there is anything unclear about them (show statements)."

2\. a. "Which of the statements best describes what you should do when you want to make a left turn at an intersection with signals that look like this (choose sign or no sign set of signals randomly and show first signals, random order)?"

b. through g. Repeat Question 2. a. for second through eighth signals, random order.

3\. "What does this sign mean (show WAIT DELAYED SIGNAL)?"

4\. a. "Engineers must often choose between these types of signals at an intersection (show first pair of 0, 3, and 5 chosen randomly). Which set do you prefer, or do you have no preference for either type of signal?"

b. "What are the reasons you prefer no/that type of signal?"

5\. a. and b. Repeat Questions 4. a. and b. for the second pair of signals.

Figure 1, continued.

6. a. and b. Repeat Questions 4. a. and b. for the third pair of signals.

7. a. "Engineers must also choose between having the left turn arrow before/after (choose randomly) and before/after the through traffic gets their green signals. This is an example of a sequence when the left-turn arrow is given before/after (show appropriate signals) and this is an example of a sequence when the arrow is given before/after (show appropriate signals). Which sequence do you prefer, or do you have no preference for either signal sequence?"

   b. "What are the reasons you prefer no/that signal sequence?"

8. "I need just three more pieces of information to complete the survey. First, the average Indiana motorist drives about 10,000 miles per year. About how many miles do you drive in an average year?"

9. "In which county do you live?"

10. "Finally, which of these age groups currently applies to you (show age ranges)?"

"The survey is complete. Do you have any questions or comments?"

"Thank you for your help with the survey. Here are your ride coupons. Enjoy your stay at the fair."

Figure 1, continued.

Left Turn Signal Project - Motorist Questionnaire Responses

Asking: Recording: Date: Place:

Question Number	Resp. No.	varies									
	Sex	1=m, 2=f									
	Time	varies									
1. a.	3	1=no, 2=yes									
b.	5	1=no, 2=yes									
2.	3 sign		no	arr	arr	no	no	lts	lts	arr	lts
	5 sign		no	gr	no	gr	●	●	gr	●	no
a.	0 R	1-4, 9=unk.									
b.	0 G	1-4, 9=unk.									
c.	3 RA	1-4, 9=unk.									
d.	3 G	1-4, 9=unk.									
e.	3 GA	1-4, 9=unk.									
f.	5 RA	1-4, 9=unk.									
g.	5 G	1-4, 9=unk.									
h.	5 GA	1-4, 9=unk.									
3.	WAIT	1-3									
4. a.	0 or 3	0, 3, 9=no									
b.	Reason	1-9									
5. a.	0 or 5	0, 5, 9=no									
b.	Reason	1-9									
6. a.	3 or 5	3, 5, 9=no									
b.	Reason	1-9									
7.	3 or 5 seq.	3, 5									
a.	B or A	1=b,2=a,9=no									
b.	Reason	1-9									
8.	Miles	varies (000)									
9.	County	1-92									
10.	Age	1-7, 9=no									

CHOICES: 3.) 1=correct, 2=unsure, 3=wrong. 4-7 b.) 1=safer, 2=less delay, 3=less confusion, 4=don't like changes, 5=more like normal, 6=all signals should look alike, 7=unsure, 8=other, 9=no response.

Figure 2. Survey response collection form.

Table 1. Signal displays, action choices offered, and error definitions for the understanding portion of the survey.

Display	Choice Number*		
	Correct	Close (Conservative) Error	Gross Error
Permissive - red ball	4	3	1,2
Permissive - green ball	2	3	1,4
Protected - green ball for through, red ball for left	4	3	1,2
Protected - green ball for through, green arrow for left	1	2	3,4
Protected - red ball for through, green arrow for left	1	2	3,4
Protected / Permissive - green ball	2	3	1,4
Protected / Permissive - green ball for through, green arrow for left	1	2	3,4
Protected / Permissive - red ball for through, green arrow for left	1	2	3,4

* 1= Turn left without stopping because you have the right-of-way.

2= Turn left without stopping unless you must wait for oncoming traffic to clear.

3= Stop. Then, turn left when oncoming traffic clears.

4= Stop. Do not turn until the signal changes to indicate you may proceed.

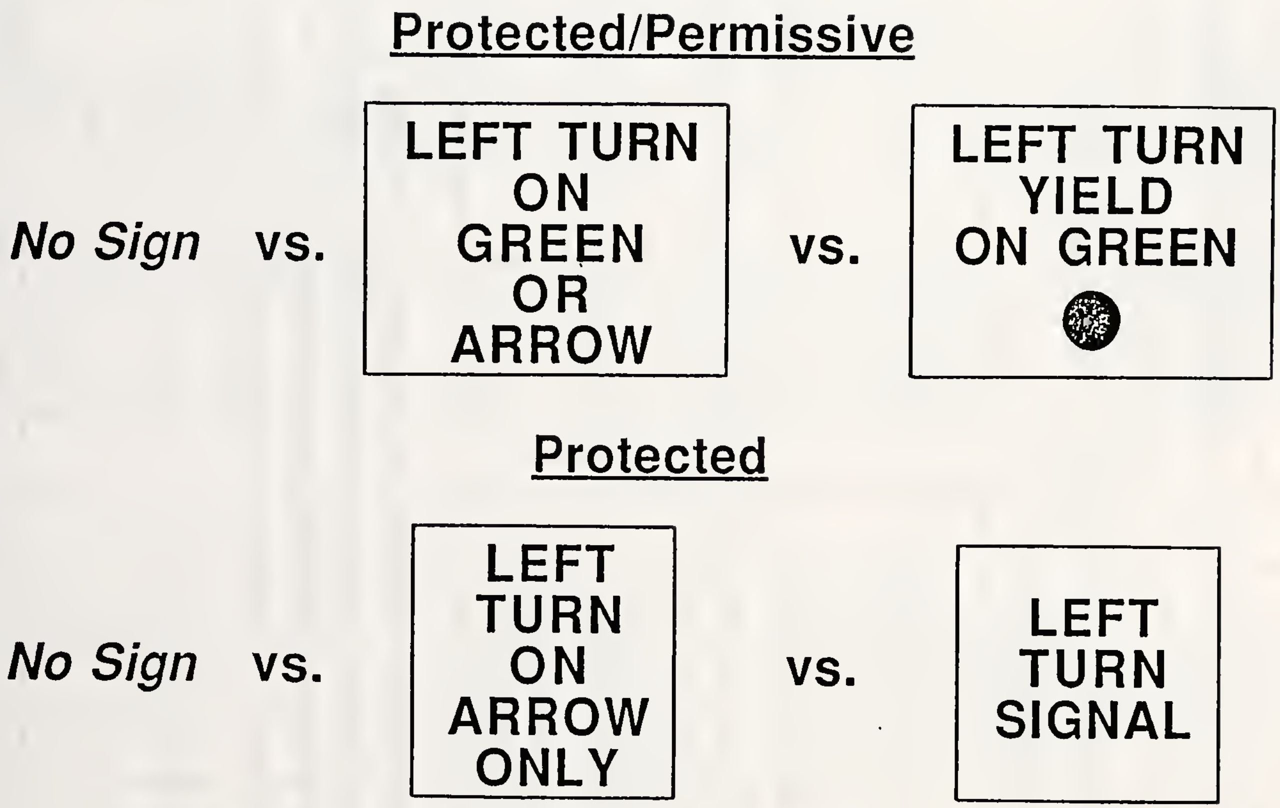


Figure 3. Sign conditions tested during survey.

versus protected, permissive versus protected-permissive, protected versus protected-permissive, and leading versus lagging sequences. Within each of the major areas of survey questions mentioned above (understanding and preferences), the order of particular questions was randomized between respondents to avoid bias. The survey also included questions designed to familiarize the respondents with the displays and survey methodology and questions to gain basic demographic data on the respondent population.

The displays shown to the respondents as questions were asked were eight and one-half by eleven-inch black-and-white copies of a hypothetical intersection with the appropriate signals or sign representing the left turn alternative. An actual display was slightly larger than the sample display given in Figure 4 and otherwise differed only in that the active signal lenses were colored (red, yellow, or green). The design of the displays was based on the displays developed for another recent survey of motorist understanding of left turn signals [Freedman and Gilfillian 1988]. The major advantage of the displays used was that they conveyed the idea of the left turn alternative in the context of a "typical" intersection (a four-lane divided street with left turn bays meeting a minor street) without distracting background noise, since the main points of the survey were understanding and preference rather than perception. However, since the displays were static, changes in signal indication were difficult to depict. Figure 5 shows one of the displays developed for the leading or lagging preference question, for which the signal sequence was the main point of the presentation.

The interviews were conducted during the hours of 9:00 a.m. to 5:00 p.m. on the first four days of the 1988 Indiana State Fair (i.e., Wednesday, August 17 through Saturday, August 20). The State Fairgrounds are in Indianapolis,

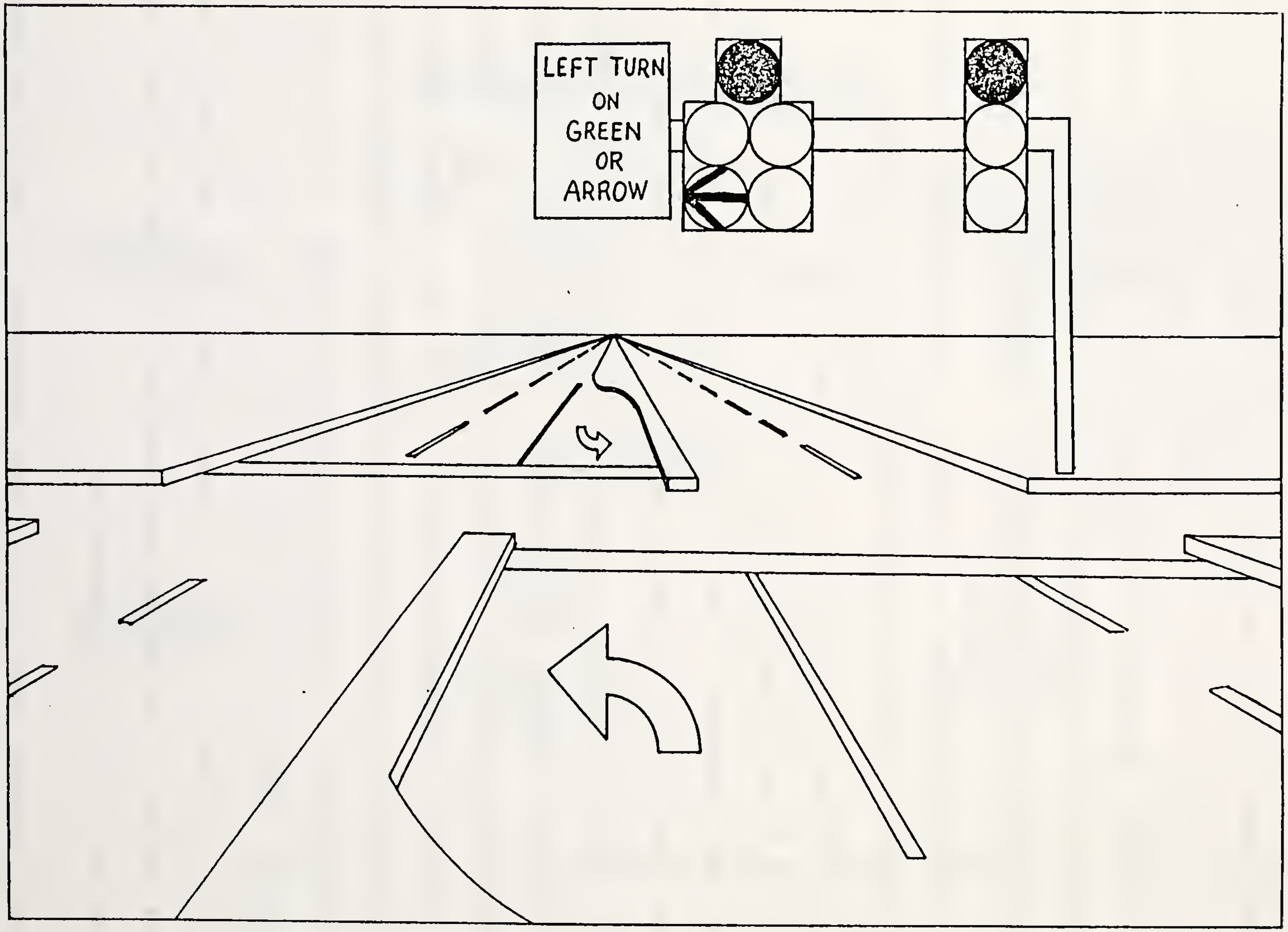


Figure 4. Typical survey display.

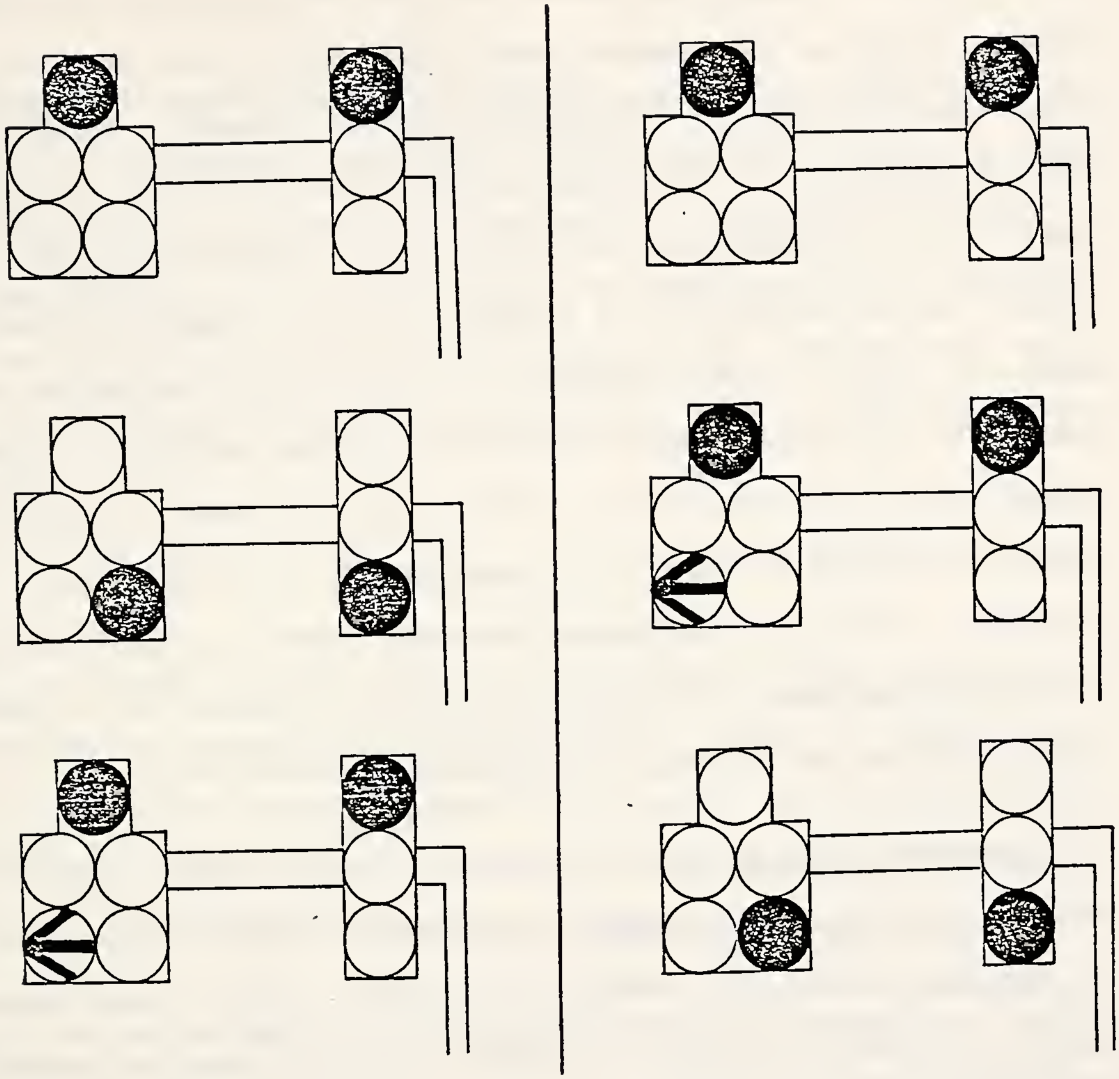


Figure 5. Leading versus lagging sequence preference display.

so the Fair attracts many people from that metropolitan area. However, the central location of Indianapolis in the state and the wide variety of different exhibits attract many different types of people to the Fair from all parts of the State. The interviews were conducted at a table on the second floor of the 4-H Exhibit Hall in an area devoted otherwise to arts and crafts displays and demonstrations. The location proved advantageous because a steady number of people walked past the table and because there was no particular bias evident in the population of passers-by towards traffic or highways (as opposed to a location near the INDOT booth, for example, which might have attracted respondents particularly interested in, or unhappy about, traffic or highways). The booth was adorned with mock "STOP" signs and traffic signals and posters explaining the general purposes of the survey (i.e., traffic signals and safety) and the names of sponsoring organizations.

Respondents were procured in two ways. First, persons walking by the table who took an obvious interest in the posters and signs were asked by survey personnel whether they wished to participate. Most of these persons were eager to help with the survey. The second method of procuring respondents was idle interviewers asked each adult passer-by to participate in the survey. This method yielded many respondents, though the "non-response" rate was much higher. Although statistics on non-response were not maintained, it was estimated by survey personnel that about half of the persons asked to participate without first expressing an interest refused to do so. The bias introduced to the survev results by these refusals was very small, however, because the reasons people gave for not responding had nothing to do with the survey purpose and because the exact survey purpose (i.e., left turn traffic signals) was not revealed until some expression of interest was shown by a potential

respondent.

Respondents received three fair amusement coupons (worth $0.45 each) for completing the interview. Interviews lasted five to ten minutes, and were conducted by graduate students in the transportation engineering program in the Purdue School of Civil Engineering. The interviewers were thoroughly briefed before the survey commenced and were encouraged to repeat the script (Figure 1) as closely as possible with each respondent to avoid bias between interviewers.

Results

After an initial "warm-up" period for interviewers on the first day of the survey, the survey proceeded without problems or changes. During the four survey days, 402 responses were recorded. The complete set of coded survey response data is provided in Appendix A. All respondents were licensed drivers or holders of learner's permits who claimed an Indiana address.

The survey respondents were representative of the population of Indiana drivers in several ways but differed from the population of Indiana drivers in several other ways. The most significant way in which the sample was representative of Indiana drivers in general was the distribution of the residences of the respondents. The breakdown of reported county of residence revealed that responses were received from people living in 85 of the 92 counties in Indiana. The ages reported by respondents also revealed a wide distribution. Table 2, showing the breakdown of the responses to the question on age, reveals that the most frequent response and the 50th-percentile response was for the "36 to 45 year" age group and that younger and older drivers were well represented. The reported mileage driven by respondents was also

Table 2. Respondent age distribution.

Age Group, Years	Number of Responses	Percent of Total Responses	Percent of Licensed Drivers*
16-25	94	23.4	21.4
26-35	84	20.9	23.8
36-45	150	37.3	18.2
46-55	44	10.9	13.2
56-65	22	5.5	12.6
66 or over	8	2.0	10.8
Total	402	100.0	100.0

* Estimate for the year 1984 from unpublished FHWA data and Bureau of Census reports.

representative of the general population, which was not surprising considering that the question on the subject was worded to mention the general "average" mileage of 10,000 per year. The median number of annual miles driven reported was 10,000 and the mean number of annual miles driven was 14,000 on a range of 100 to 100,000 miles per year. Fifty-seven percent of survey respondents were female, while 49 percent of licensed vers in Indiana (in 1984) were female [U. S. Bureau of Census 1986]. The survey was not especially representative for the proportion of urban to rural area residents responding. Only 51 percent of the respondents were from "urban" counties (defined as belonging to Standard Metropolitan Statistical Areas) as opposed to the statewide 1980 population figure of 67 percent [U. S. Bureau of the Census 1982]. In sum, although the survey sample included higher proportion of female and rural people than the general Indiana population, the sample generally represented the population considering that it was gathered in one place over a limited time.

Error Rate

The quality of the responses to the survey was judged partially by an analysis of the "error rate" on the questions testing motorist understanding. Table 3, which gives the number of errors (i.e., incorrect responses of any type) committed by the respondents on the nine understanding questions (Questions 2 and 3 on the script in Figure 1), shows that the number of errors was well distributed. Few people entirely misunderstood the survey methodology or displays, since only two people got all nine questions wrong and only 20 people got seven or more questions wrong. Table 3 also shows that the survey questions were not too easy, since only 48 respondents gave correct responses for all nine questions. Since most respondents made errors on a few questions, it is likely that differences between displays caused respondents to

Table 3. Distribution of numbers of errors on nine understanding questions.

Number of Errors	Number of Respondents	Percent of Total
0	48	11.9
1	49	12.2
2	72	17.9
3	85	21.1
4	52	12.9
5	45	11.2
6	31	7.7
7	11	2.7
8	7	1.7
9	2	0.5
Total	402	100.0

err, as had been hoped, rather than flaws in the survey methodology.

The error rate on the nine understanding questions was analyzed with other variables to see whether patterns of errors emerged. Of special interest was the relationship between the error rate on the nine understanding questions and the particular interviewer, and between the error rate and the day the interview was conducted. Using SAS [SAS Institute, Inc. 1985] to compute the chi-square value as a test of the degree of association between the error rate and the particular interviewer, the significance probability (i.e., "p") was found to be 0.838 which shows that the two variables were not related at the 0.05 level of significance. The chi-square significance probability for the association between the error rate and the day of the interview was 0.924, which shows that those two variables were also not closely related. Both of the above findings lend credence to the view that the quality of the survey data was high.

The error rate was also tabulated with respondent characteristics including age, sex, urban or rural county of residence, and annual miles driven. The resulting significance probabilities of 0.390 with the age variable, 0.336 with the sex variable, 0.075 with the urban or rural county of residence variable, and 0.041 with the annual miles driven variable show that only the latter was significantly associated with the error rate at the 0.05 level. A close look at the error rate versus annual miles driven data revealed no specific pattern between the variables, however, and attempts to build a model of the relationship yielded very poor results.

Understanding and Sign Conditions

The results for the understanding portion of the survey regarding signing

conditions are summarized in Tables 4 and 5 for the six signal displays which had variable signing conditions. The results for the protected signal displays on Table 4 show that no particular pattern was prevalent for the relative understanding of the "no sign" condition, the "LEFT TURN ON ARROW ONLY" sign, and the "LEFT TURN SIGNAL" sign. Even for the simultaneous green ball and green arrow display, which boasts a chi-square significance probability of 0.022 (indicating a significant relationship at the 0.05 level) the "no sign" condition was just slightly superior to the other sign conditions and there is little to distinguish the performance of the "LEFT TURN ON ARROW ONLY" sign from the performance of the "LEFT TURN SIGNAL" sign. From Table 5 for the protected-permissive signal displays a clear pattern emerges with the "LEFT TURN YIELD ON GREEN OR ARROW" sign performing better than the "no sign" condition and performing much better than the "LEFT TURN YIELD ON GREEN @" sign. The latter sign was associated with far fewer correct answers, far more conservative errors, and far more gross errors of understanding than the other two signing conditions for protected-permissive signals when a green ball for through traffic and a green arrow for left turns were displayed.

Understanding of Signals

The eight understanding questions in Question 2 of the survey were analyzed using four comparisons of the relative understanding of different signal schemes. Tables 6 through 9 show the data and the statistical test results for these four comparisons. Table 6 shows that the permissive and the protected-permissive signal schemes, when both were displayed with green ball signals, generated almost identical numbers of correct responses but that the permissive scheme had a significantly greater proportion of close

Table 4. Understanding of sign display alternatives for a protected signal.

Signal Display	Sign Display	Response Class: Correct Responses	Close Errors	Gross Errors	Total Responses	p-value
Green Ball for Through Traffic, Red Ball for Left Turns	No Sign	125	8	2	135	0.504*
	"Left Turn on Arrow Only"	126	5	2	133	
	"Left Turn Signal"	122	6	6	134	
	Total	373	19	10	402	
Green Ball for Through Traffic, Green Arrow for Left Turns	No Sign	97	29	9	135	0.022
	"Left Turn on Arrow Only"	97	19	17	133	
	"Left Turn Signal"	86	39	9	134	
	Total	280	87	35	402	
Red Ball for Through Traffic, Green Arrow for Left Turns	No Sign	99	24	12	135	0.173
	"Left Turn on Arrow Only"	102	14	17	133	
	"Left Turn Signal"	103	23	8	134	
	Total	304	61	37	402	

* For a chi-square analysis in which the close (conservative) error and gross error columns were combined.

Table 5. Understanding of sign display alternatives for a protected-permissive signal.

Signal Display	Sign Display	Response Class: Correct Responses	Close Errors	Gross Errors	Total Responses	p-value
Green Ball for Through Traffic and Left Turns	No Sign	54	50	30	134	0.213
	"Left Turn on Green or Arrow"	68	33	34	135	
	"Left Turn Yield on Green ●"	58	46	29	133	
	Total	180	129	93	402	
Green Ball for Through Traffic, Green Arrow for Left Turns	No Sign	88	36	10	134	< 0.0005
	"Left Turn on Green or Arrow"	93	27	15	135	
	"Left Turn Yield on Green ●"	56	47	30	133	
	Total	237	110	55	402	
Red Ball for Through Traffic, Green Arrow for Left Turns	No Sign	80	28	26	134	0.026
	"Left Turn on Green or Arrow"	92	16	27	135	
	"Left Turn Yield on Green ●"	71	37	25	133	
	Total	243	81	78	402	

Table 6. Relative understanding of permissive and protected-permissive signals when only a green ball is displayed.

Response Class	Signal	Number of Responses	Proportion of (402) Responses	Z Computed	Significant Difference at 0.05 Level?
Correct	Permissive	181	0.450	0.06	No
	Protected / Permissive	180	0.448		
Close (conservative) Error	Permissive	179	0.445	3.70	Yes
	Protected / Permissive	128	0.318		
Gross Error	Permissive	42	0.104	4.60	Yes
	Protected / Permissive	94	0.234		

Table 7. Relative understanding of permissive and protected signals when only a red ball is displayed.

Response Class	Signal	Number of Responses	Proportion of (402) Responses	Z Computed	Significant Difference at 0.05 Level?
Correct	Permissive	336	0.836	4.04	Yes
	Protected	373	0.928		
Close (conservative) Error	Permissive	55	0.137	4.39	Yes
	Protected	19	0.047		
Gross Error	Permissive	11	0.027	0.22	No
	Protected	10	0.025		

Table 8. Relative understanding of protected and protected-permissive signals when a green ball for through traffic and a green arrow for left turns are displayed.

Response Class	Signal	Number of Responses	Proportion of (402) Responses	Z Computed	Significant Difference at 0.05 Level?
Correct	Protected	280	0.696	3.15	Yes
	Protected / Permissive	237	0.590		
Close (conservative) Error	Protected	87	0.216	1.89	No
	Protected / Permissive	110	0.274		
Gross Error	Protected	35	0.087	2.23	Yes
	Protected / Permissive	55	0.137		

Table 9. Relative understanding of protected and protected-permissive signals when a red ball for through traffic and a green arrow for left turns are displayed.

Response Class	Signal	Number of Responses	Proportion of (402) Responses	Z Computed	Significant Difference at 0.05 Level?
Correct	Protected	304	0.756	4.61	Yes
	Protected / Permissive	243	0.604		
Close (conservative) Error	Protected	61	0.152	1.85	No
	Protected / Permissive	81	0.202		
Gross Error	Protected	37	0.092	4.13	Yes
	Protected / Permissive	78	0.194		

(conservative) vative) errors (at the 0.05 level using the Z-test for proportions [Bhattacharyya and Johnson 1977]) and a correspondingly smaller number of gross errors. Table 7 shows that the protected scheme inspired a significantly greater number of correct responses than the permissive scheme when both were displayed with red ball signals. Finally, for displays with a green left turn arrow and green ball signals for through traffic (Table 8) and a green left turn arrow and red ball signals for through traffic (Table 9), the protected signal scheme had significantly more correct responses, significantly fewer gross errors, and marginally fewer conservative errors than the protected-permissive scheme. From the results, the relative levels of understanding of the signal schemes tested is very clear: protected signals were the best understood, permissive signals were less well understood, and protected-permissive signals were the least understood.

The data from the understanding portion of the survey were also examined to see which signal phases for the protected, protected-permissive, and permissive signals were most misunderstood. From Tables 6 and 7 for the permissive signal it can be seen that the green ball phase was far more often misunderstood (181 correct responses) than the red ball phase (336 correct responses). Tables 7, 8, and 9 show that the protected signal most often inspired a correct response when respondents viewed a red ball (373 correct responses), while the difference between the other two phases tested was not significant (the green arrow with red ball had 304 correct responses and the green arrow with green ball had 280 correct responses). Finally, while none of the three phases of the protected-permissive signal tested generated a high number of correct responses, the green ball phase (Table 6, 180 correct responses) was the most misunderstood. The green arrow with red ball phase

(Table 9) had about the same number of correct responses as the green arrow with green ball phase (Table 8), but since the green arrow with red ball phase also had significantly more gross errors (78 to 55) it should be considered the more misunderstood of the two on the basis of these survey data.

Preferences for Signal Alternatives

A summary of the survey responses to the four preference questions (Questions 4 through 7) is provided in Table 10. Those data show that the protected signal was clearly preferred over the permissive signal and the protected-permissive signal, the protected-permissive signal was preferred by more respondents than the permissive signal, and the leading signal sequence was preferred more often than the lagging sequence. For all the comparisons in Table 10, 95- percent confidence intervals on the proportion of respondents choosing one or the other signal alternative [Bhattacharyya and Johnson 1977] lie outside 0.5, meaning that the differences expressed between alternatives are all significant at the 0.05 level. The preference for leading over lagging sequences was not as strong as the confidence interval would indicate, though, since almost 100 respondents had no preference.

A summary of the breakdown of preference responses is provided in Table 11 which shows that most of the preference results were unrelated to the variables examined. Age was found to be related to the preference of protected or protected-permissive signals, with people in the 16 to 25-year group preferring a protected-permissive signal more often. Age was somewhat (p=0.054) related to preference of leading or lagging sequence, although the main contributor to the high chi-square value in this case was the tendency of younger drivers to have no preference more often. The urban or rural county of

Table 10. Preference questions summary.

Signal Alternatives	Number of Respondents Expressing a Preference	Respondents Preferring Alternative		Confidence Interval (0.05 level)	
		Number	Proportion	Lower Limit	Upper Limit
Protected	391	382	0.977	0.962	0.992
Permissive		9	0.023	0.008	0.038
Protected	364	312	0.857	0.821	0.893
Protected / Permissive		52	0.143	0.107	0.179
Permissive	376	39	0.104	0.073	0.135
Protected / Permissive		337	0.896	0.865	0.927
Leading	307	248	0.808	0.764	0.852
Lagging		59	0.192	0.148	0.236

Table 11. Relationships between preferences for signal alternatives and various independent variables (expressed as chi-square significance proportion).

Variable	Preference Question		
	Protected vs. Protected / Permissive*	Permissive vs. Protected / Permissive*	Leading vs. Lagging
Age	< 0.0005	0.240	0.054
Sex	0.224	0.704	0.126
Urban or Rural County of Residence	0.500	0.848	0.002
Annual Miles Driven	0.060	0.791	0.056
Interviewer	0.293	0.779	0.019
Day of Interview	0.493	0.295	0.224
Number of Errors on Nine Understanding Questions	0.140	0.394	0.526
Number of Errors on Three Understanding Questions with Protected/Permissive Signals	0.632	0.109	Not Applicable
Number of Errors on Three Understanding Questions with Protected Signals	0.268	Not Applicable	Not Applicable

* Chi-square values were calculated from tables which did not include "no preference" responses.

residence variable was found to be related to the preference for leading or lagging sequence, with people from rural counties expressing a preference more often for the lagging sequence. The preference for protected or protected-permissive signals was somewhat (p=0.060) related to the annual miles driven, with respondents driving the least showing greater preference for protected-permissive signals. The annual miles driven variable was also somewhat (p=0.056) related to the preference for leading or lagging signals, with the people driving the least opting for the lagging sequence or the no preference alternatives more often. Finally, the particular interviewer was found to be related to the results for the leading or lagging question. Fortunately, the trend which emerged in this relationship involved one interviewer who recorded a sizeable number of no preference responses and another interviewer who recorded very few no preference responses, so the data for the leading and lagging sequences themselves did not depend on particular interviewers. It reflects well on the quality of the survey that the interviewer was unrelated to the results for the other questions shown in Table 11 and that the day on which a particular interview was conducted was unrelated to the results for all the preference questions.

A summary of the reasons for preferences expressed by respondents is given in Table 12. Respondents overwhelmingly cited the protected signal for causing less confusion when they expressed a preference for it over both the permissive and the protected-permissive signal. The protected signal was also preferred over the permissive signal by many respondents because it was perceived as safer and as causing less delay. Reasons given by respondents for preferring protected-permissive over permissive signals broke down in a very similar manner, with "less confusion" given predominantly and "safer" and

Table 12. Summary of numbers of respondents citing various reasons for expressed preferences.

Preference	Reason				
	Safer	Less Delay	Less Confusion	More Like Normal	Unsure or Other
Protected	69	52	276	8	8
vs.					
Permissive	0	3	4	0	2
Protected	8	5	280	11	12
vs.					
Protected / Permissive	2	17	21	5	10
Protected / Permissive	50	59	229	13	12
vs.					
Permissive	0	2	31	1	5
Leading	61	65	27	73	39
vs.					
Lagging	11	17	11	10	11

"less delay" given by some. The reasons respondents gave for preferring leading over lagging sequences were well distributed, with roughly equal numbers of respondents stating that leading sequences were more like normal (i.e., more common), safer, and associated with less delay.

Other Results

During the survey, data were recorded on the respondents' understanding of the "WAIT DELAYED SIGNAL" sign (Question 3 on the script shown previously in Figure 1). A display with a permissive signal and the sign was shown, and the respondents were asked in an open-ended fashion to explain what the sign meant. The response was judged by the interviewer to be either "correct," "unsure," or "wrong." The final tally of responses showed that 260 respondents were judged to have given correct responses, 58 respondents were judged to be unsure of the meaning of the sign, and 84 respondents provided answers which were judged to be wrong. Drawing firm conclusions from these data is not advisable, however, due to the subjective nature of the judgement made by the interviewers and due to the fact that there are no relative data with which to compare these results (i.e., no competitor sign was tested).

Data were also collected on the respondents' claims of familiarity with the protected and the protected-permissive signals (Question 1 on the script given previously in Figure 1). Because the question was asked primarily to initiate the respondents in the survey method and displays and because many respondents later changed their minds about their previous familiarity (i.e., "I guess I have seen those signals around after all"), the data from Question 1 were not extensively analyzed.

Chapter Summary

The survey of Indiana drivers conducted for this project at the 1988

Indiana State Fair provided usable results on the understanding of and preferences for various left turn signal alternatives. Despite the fact that the survey was conducted in one place over a four-day span, responses were received from a wide variety of different people. The error rate computed for the nine understanding questions, and the lack of association between preferences expressed and particular interviewers or survey days, showed that the survey script, displays, and format were reasonable and that the data were not biased in any substantive way. However, applications of the survey data outside this project must be made carefully with the context of the survey (i.e., the tendencies of Indiana drivers and highways in 1988, the four-lane boulevard shown in the survey displays, etc.) in mind.

Several results cited in the previous pages are particularly notable. The protected signal was by far the best understood, while the protected-permissive signal was the least understood. The "LEFT TURN YIELD ON GREEN @" sign proved more confusing than the other protected-permissive signing alternatives tested, while there was little to distinguish the protected signal signing alternatives tested. The protected signal was the most preferred signal because most respondents associated it with less confusion, while the permissive was the signal which was least preferred. Finally, for a wide variety of reasons, respondents expressed a greater preference for the leading over the lagging sequence.

CHAPTER 4 - TRAFFIC CONFLICTS

Introduction

The relative safety afforded by leading and lagging signal sequences has not been well documented. To help overcome that gap, a traffic conflict study was conducted at six intersections in Indianapolis for this project. The study method and results are described in this chapter and the conclusions are used in Chapter 7 to help establish guidelines for the placement of the various left turn signal alternatives.

Traffic conflicts are events "involving the interaction of two or more road users, usually motor vehicles, where one or both drivers take evasive action such as braking or weaving to avoid a collision" [Parker and Zegeer 1988]. Traffic conflict data have been shown to be highly correlated with accident data in many traffic situations [Parker and Zegeer 1988]. Consequently, traffic conflicts have often been used as a proxy for accident data which require a long period of collection [Parker and Zegeer 1988]. For this project, there were insufficient sites to set up a comparative parallel study of accident data, although some left turn accident data are presented in Chapter 5. Also, there was insufficient time during the study period in which a before and after study of accident data could be arranged, so a conflict study was advantageous.

Traffic conflict studies have been effective in previous analyses of left turn treatments. In Kentucky, traffic conflicts involving left-turning vehicles were studied at 25 intersections to help determine guidelines for the installation of left turn lanes [Agent 1979b]. In Virginia, conflicts involving left-turning vehicles were studied at ten different intersections with

protected-permissive signals to help develop guidelines for the placement of such signals [Perfater 1983]. The review of previous literature conducted for this project revealed no traffic conflict data on leading versus lagging left turn phases, however.

Methodology

A before and after study of the change from lagging to leading sequence using traffic conflicts was originally planned for this project. The first step in that original plan was the compilation of a list of signals in Indiana with lagging sequences. However, only 16 such intersections were identified during an exhaustive search of the state highway system and the larger city street systems. Most of the 16 were in the downtown Indianapolis area where changing the phasing sequence could have interfered with an elaborate signal control system, so the original before and after study plan was not pursued. Since the literature review had revealed the strong possibility that changes from leading to lagging signal sequence would result in more accidents, a study plan to evaluate traffic conflicts before and after that type of change was not adopted. Instead, a plan to compare traffic conflict rates at intersections with lagging signals to rates at similar intersections with leading signals was implemented. This study plan allowed meaningful conclusions on leading and lagging sequences to be made without the difficulties incumbent with retiming signals in an existing network.

Three pairs of intersections (a "pair" consisted of one intersection with a protected-permissive signal and one intersection with a permissive-protected signal) were identified for the study. The important characteristics of these intersections are shown in Table 13. The characteristics matched very well

Table 13. Characteristics of intersections used in conflict study.

Characteristic	Downtown pair	Urban pair	Suburban diamond pair
Name, two-way street, lead	Ohio	South	86th
Name, one-way street, lead	Delaware	Delaware	NB Key-stone Ramp
Name, two-way street, lag	Washington	Meridian	86th
Name, one-way street, lag	Delaware	12th	SB Key-stone Ramp
Distance between lead and lag intersections, miles	0.2	2	0.1
Distance from city center, miles	0.2	1	10
Pedestrians	Many	Few	None
Number through approach lanes	2-4*	2	2
Left turn lane	No	Yes	Yes
Right turn on red	No	No	Yes
Right turn lane and/or channel	Neither	Neither	Both
Posted speed limit, mph, lead	25	30	40
Posted speed limit, mph, lag	25	35	40
Cycle length, seconds	70	70	60,80
Left turn signal lens arrangement, lead	5-head doghouse	5-head doghouse	5-head doghouse
Left turn signal lens arrangement, lag	4-head stacked	5-head doghouse	5-head doghouse

* Two on Ohio during 0900 to 1500, three on Ohio during 0730 to 0900 and 1500 to 1800, three on Washington during 0900 to 1500, and four on Washington during 0730 to 0900 and 1500 to 1800.

between members of the pairs. The match between the intersections in the "suburban diamond" pair was especially close, since that pair consisted of the two ramp terminals of a diamond interchange which lie along the same street only about 500 feet apart. The characteris tics of the "downtown" and the "urban" pairs of intersections tions matched well but less closely than the suburban diamond pair. The three pairs of intersections studied generally represent a good variety of conditions for which the leading versus lagging question is relevant.

The traffic conflict study was completed in September and October of 1988. All observations were made in dry weather. Approximately eight hours of observations on a single day (generally 0730 to 0930, 1100 to 1400 and 1500 to 1800) were made at each intersection. Both members of a pair of intersections were observed on the same day of the week. The observations proceeded smoothly at five of the intersections. However, at the sixth intersection a landscaping crew began working near the intersection at about 1100 and disrupted traffic flow, so the conflict study at that intersection from 1100 to 1400 and 1500 to 1800 was completed a week later.

Two observers recorded conflicts manually as they viewed traffic from opposite sides of an intersection. One observer was positioned near the approach with the left- turning traffic of interest for all six intersections, to promote consistent data recording. The other observer was positioned near the approach with the traffic opposing the left turn of interest. Traffic on the cross-street (i.e., the one-way street or ramp) was not of interest during the conflict study and no effort was made to observe it. The observers were generally inconspicuous to passing traffic, especially at the urban and downtown intersection pairs where there was a great deal of background activity in

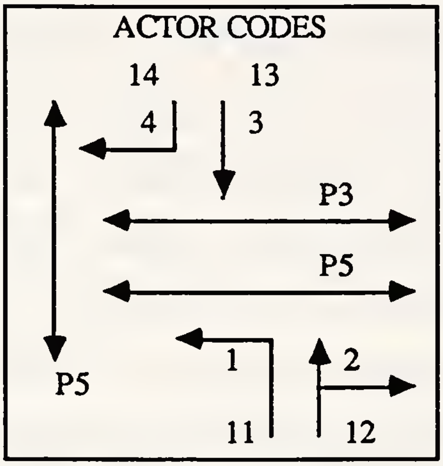
the view of a driver. The observers were all graduate students in the Purdue University transportation engineering program.

The form used to record traffic conflicts evolved after extensive pilot testing and is given in Figure 6. The specific types of data recorded included the times of particular conflicts, the desired paths of the vehicles involved in the conflict (i.e., left-turning, right-turning, etc.) and the descriptions of the movements of the vehicles during the conflict. Observers recorded data on all unusual traffic events witnessed (i.e., sudden stops, weaves, horn honking, etc.), using the codes on the form to describe actions of vehicles or writing notes if no codes were available to adequately describe the actions. Traffic volumes for the movements of interest during the periods of data collection were also recorded--the observer near the left turn approach manually recorded the number of vehicles making left turns and going straight from that approach, and the observer near the approach with opposing vehicles manually recorded the number of vehicles making right turns and going straight from that approach. Both observers also noted the number of signal cycles with and without pedestrians crossing the approach to which the left-turning vehicles of interest were destined.

Results

As was previously noted, observers recorded every unusual traffic event witnessed at the six intersections regardless of the relationship of the event to left turns or the signal sequence. When the raw data were analyzed, however, only data for the traffic conflict types which were related to left turns or the signal sequence were retained. The most important of these retained conflict types, based on previous studies of left turn treatments

LEFT TURN PROJECT CONFLICT DATA



ACTION CODES

← = Hestitate on green arrow

H=Hesitate on green ball

R=Ran red

S=Stop

D=Decelerate

A=Accelerate

B=Back up

W=Weave

Name:

Date:

Time Period:

Intersection:

Direction (leg with actor 1):

Weather:

Time	Actor 1	Action	Actor 2	Action	Comments

Figure 6. Traffic conflict data collection form.

using traffic conflicts [Agent 1979b and Perfater 1983], were:

- A left-turning vehicle interacting with an oncoming through vehicle (e.g., "left and oncoming"),

- A left-turning vehicle interacting with a pedestrian crossing the approach onto which the vehicle is turning (e.g., "left and pedestrian"),

- A left-turning vehicle hesitating or starting and then stopping suddenly when presented with a green ball signal and no oncoming traffic or with a green arrow signal (e.g., "indecision left"), and

- A left-turning vehicle crossing the stop bar and entering the intersection on a red ball signal (e.g., "run red left").

Other types of conflicts which were also retained and analyzed but were deemed much less important than those listed above included indecision and run red conflicts by vehicles on the approaches of interest which were not turning left.

Table 14 contains the data and a statistical summary for the more important types of conflicts and Table 15 contains the same information for the less important types of conflicts. The data in Table 14 show that numbers of conflicts sufficient for analysis were recorded during the periods of observation for almost every conflict type at each intersection. Table 14 also shows that the numbers of left-turning vehicles were very similar between members of the suburban diamond pair, and quite different for members of the downtown

Table 14. Left turn conflict results.

Intersections	Conflict type	Signal sequence	No. of conflicts	No. of left turns	Proportion of left turns in conflicts	Z computed	Significant difference at 0.05?
Downtown	Left and pedestrian	Lag	11	1828	.0060	-6.01	Yes
		Lead	33	892	.0370		
	Left and oncoming	Lag	23	1828	.0126	-2.69	Yes
		Lead	24	892	.0269		
	Indecision - left	Lag	30	1828	.0164	0.36	No
		Lead	13	892	.0146		
	Run red - left	Lag	10	1828	.0055	Fisher's test used	No
		Lead	4	892	.0045		
Urban	Left and oncoming	Lag	9	1073	.0084	-2.49	Yes
		Lead	22	1022	.0215		
	Indecision - left	Lag	24	1073	.0224	1.12	No
		Lead	16	1022	.0157		
	Run red - left	Lag	9	1073	.0084	0.40	No
		Lead	7	1022	.0068		
Suburban diamond	Left and oncoming	Lag	17	1322	.0129	-0.51	No
		Lead	16	1044	.0153		
	Indecision - left	Lag	48	1322	.0363	2.80	Yes
		Lead	18	1044	.0172		
	Run red - left	Lag	5	1322	.0038	-2.79	Yes
		Lead	15	1044	.0144		

Table 15. Conflict results for vehicles not turning left.

Intersections	Conflict type	Signal sequence	No. of conflicts	No. of vehicles observed	Proportion of vehicles in conflicts	Z computed	Significant difference at 0.05?
Downtown	Indecision - other	Lag	30	9913	.0030	-2.20	Yes
		Lead	28	5237	.0054		
	Run red - other*	Lag	22	9913	.0022	0.91	No
		Lead	8	5237	.0015		
Urban	Indecision - other	Lag	39	11990	.0032	-1.58	No
		Lead	29	6080	.0048		
	Run red - other	Lag	40	11990	.0033	-1.79	No
		Lead	31	6080	.0051		
Suburban diamond	Indecision - other	Lag	26	11680	.0022	-0.15	No
		Lead	34	14548	.0023		
	Run red - other	Lag	27	11680	.0023	0.26	No
		Lead	31	14548	.0021		

* Does not include the many right-turning vehicles which violated the "NO TURN ON RED" sign.

pair. The conflict rates given in Table 14 (conflicts per left-turning vehicle) were of reasonable magnitude, ranging from just under four percent to just under 0.4 percent. One of the comparisons in Table 14 did not have enough conflicts to use the Z-test, so Fisher's exact test was performed on that comparison [Bhattacharyya and Johnson 1977].

The largest difference between leading and lagging sequences seen in Table 14 was for the left and pedestrian conflicts at the downtown pair, where the leading sequence was associated with three times as many conflicts and six times as great a conflict rate as the lagging sequence. In most cases at the leading site, these left and pedestrian conflicts happened when pedestrians stepped off the curb and into the approach to which left-turning vehicles were destined upon seeing a red signal for the cross-street (ignoring the "DON'T WALK" signal). This result agrees with findings from the literature review in Chapter 2 and will be considered in developing guidelines for left turn signals.

Table 14 also shows that the lagging sequence intersection of the suburban diamond pair was associated with a significantly (at the 0.05 level) lower rate of run red left conflicts than the leading sequence intersection. Many times at the leading sequence intersection three vehicles were observed making left turns after opposing traffic had begun to stop for the yellow ball signal (e.g., three "sneakers"), with the third vehicle entering the intersection with the red ball signal showing. There was a generous supply of candidates for this behavior at the leading intersection because many vehicles wanting to make left turns joined the queue during the permissive phase of the cycle and were still in the queue as the permissive phase was ending. By contrast, at the lagging sequence intersection the available supply of left-turning

vehicles was almost always cleared on the green arrow signal so there were fewer vehicles available to run the red signal.

Another important result in Table 14 shows that the lagging sequence was associated with significantly lower rates of left and oncoming conflicts (at the 0.05 level) than the leading sequence at the downtown and urban pairs of intersections. Two alternate explanations for these differences were available based on the data. First, the number of opposing vehicles recorded at the lagging intersection downtown was 6947 versus 3285 at the leading intersection downtown; 6634 opposing vehicles were recorded at the lagging urban intersection versus 3590 at the leading urban intersection. Thus, vehicles turning left at the lagging intersections may have had fewer opportunities to turn on the green ball signal, and therefore fewer opportunities to be involved in left and oncoming conflicts. This possibility was tested by comparing the conflict rates at the leading and lagging sequence intersections for 15-minute time periods with similar oncoming volumes. The data given in Table 16 show that the lower oncoming volumes at the leading intersections may account for some but not all of the difference in conflict rates between leading and lagging signals. For the downtown pair the lagging sequence intersection had a significantly lower rate than the leading sequence intersection. For the urban pair the lagging intersection had a lower rate, but the difference was not significant.

The second explanation for the lower left and oncoming conflict rates at the lagging intersections in the urban and downtown pairs was the tendency at the leading intersections for left-turning vehicles to try to enter the intersection immediately after the yellow arrow signal had ceased as if they still had the right-of-way. These "time stealers" then interacted with the more

Table 16. Comparison of left and oncoming conflict rates for time periods with similar oncoming volumes.

Intersections	Signal sequence	Number of 15-min. periods examined	Mean number of oncoming vehicles	Proportion of left turns in conflicts	Z computed	Significant difference at 0.05?
Downtown	Lag	10	194	.0080	-2.98	Yes
	Lead	6	172	.0369		
Urban*	Lag	13	193	.0111	-0.98	No
	Lead	6	184	.0202		

* Includes the few left and pedestrian conflicts recorded.

forthright of the oncoming vehicles which had just received the green ball signal. Examination of the descriptions of particular conflicts revealed that time stealers accounted for most of the difference in conflict rates between the leading and lagging downtown and urban intersections. There were a number of time stealers at the leading suburban diamond intersection as well, but the lagging intersection of that pair had an abundance of left and oncoming conflicts caused by indecisive left-turning vehicles and the two effects cancelled each other in the final statistics.

Indecision conflicts accounted for the remaining significant differences between leading and lagging intersections seen in Tables 14 and 15. Table 14 shows that the lagging intersection was associated with a higher rate of indecision conflicts than the leading intersection at all three intersection pairs, and the difference at the suburban diamond pair was significant at the 0.05 level. Table 15 shows that the lagging intersections also had higher numbers of indecision-other conflicts than the leading intersections for two of the three pairs. However, when the indecision other conflicts were recast in terms of conflict rates per vehicle observed, the lagging intersections then had lower (significantly lower, in the case of the downtown pair) rates of indecision-other conflicts.

Examination of the data revealed that virtually all of the indecision conflicts, whether by a left-turning or other vehicle, occurred at the beginning of a signal phase. Thus, the number of signal cycles, rather than the number of vehicles observed, may have been the more appropriate available variable with which to compute a conflict rate. Table 17 shows the indecision conflict rates per signal cycle. Those data confirm that it was the lagging sequence which was associated with higher indecision conflict rates, including

Table 17. Indecision conflicts per signal cycle.

Intersections	Conflict type	Signal sequence	No. of conflicts	No. of cycles	Proportion of cycles with a conflict	Z computed	Significant difference at 0.05?
Downtown	Left	Lag	30	386	.0777	2.67	Yes
		Lead	13	386	.0337		
	Other	Lag	30	386	.0777	0.27	No
		Lead	28	386	.0725		
Urban	Left	Lag	24	386	.0622	1.30	No
		Lead	16	386	.0414		
	Other	Lag	39	386	.1010	1.27	No
		Lead	29	386	.0751		
Suburban diamond	Left	Lag	48	390	.1231	3.86	Yes
		Lead	18	390	.0462		
	Other	Lag	26	390	.0667	-1.07	No
		Lead	34	390	.0872		

significantly higher rates for the indecision left conflicts at the downtown and suburban diamond pairs.

Two basic reasons emerged to explain the generally higher rates of indecision conflicts (especially indecision-left conflicts) at lagging sequence intersections. First, left-turning vehicles which received a lagging green arrow were hesitant to begin a turn until it was absolutely clear that oncoming traffic was going to stop. This was especially true at the suburban diamond location where the speeds of oncoming vehicles were relatively high. These high speeds sometimes led to false starts by left turn vehicles, rapid decelerations by vehicles behind the left turn queue leader, horn honking, and other unusual behavior. Second, drivers of left-turning and other vehicles often seemed surprised by a lagging signal sequence, and sometimes committed false or late starts upon receiving the right-of-way. Considering that there are so few lagging sequences in Indiana, some motorist surprise is understandable.

Chapter Summary

The traffic conflict study conducted for this project provided reasonable data to compare the relative safety afforded by leading and lagging signal sequences. The three pairs of test intersections from the Indianapolis area which were selected were very similar in characteristics among pairs but provided a variety of conditions between pairs. The data were gathered manually on all unusual maneuvers from two sides of a test intersection. Sufficient numbers of the most important types of conflicts were witnessed to allow appropriate statistical tests to be employed. Applications of the data gathered during the conflict study, however, must be made carefully with the con-

text of the study in mind. The study was conducted at intersections with three approaches and in Indiana there are generally few lagging phasing sequences.

The lagging sequence, relative to the leading sequence, was associated during the observations for this study, with:

- a lower rate of left and pedestrian conflicts downtown,

- lower rates of left and oncoming conflicts, especially downtown,

- a lower rate of running red-left conflicts at the suburban diamond intersection, and

- higher rates of indecision conflicts.

The reasons for these differences were varied. The relatively higher rate of left and pedestrian conflicts at the leading intersection occurred because of pedestrians entering the intersection in violation of the "DON'T WALK" signal when the cross-street signal went to red. The relatively higher rates of left and oncoming conflicts at leading intersections were due primarily to time stealers at the end of the yellow arrow signal. The leading sequence had relatively higher rates of run red left conflicts because of the greater frequency of a third sneaker at the end of the yellow ball signal. Finally, the relatively higher rates of indecision conflicts at the lagging intersections resulted from motorist surprise at seeing the rare lagging sequence or from the hesitation of motorists to turn in front of fast oncoming vehicles.

CHAPTER 5 - ACCIDENTS

Introduction

One widely accepted measure of the traffic safety at a particular location is the accident history of the location. For this project, accident data were used to evaluate the relative safety of intersections with leading left turn sequences and similar intersections with lagging sequences. Four years of accident data were used to provide estimates of the number of accidents related to left turns which had occurred at the intersections of interest. Traffic volume counts were used to estimate exposure at each intersection and accident rates were then computed for comparison. The number of sites where accident data were collected was limited due to a scarcity of lagging signals so detailed statistical tests were not possible. Nonetheless, the relative safety analysis provided much insight.

Sample of Intersections

A large number of intersections with wide-ranging characteristics was desired for this project in both the leading and the lagging sequence categories. However, field inspections and phone conversations with engineers in five of the six INDOT districts and all the larger cities in Indiana revealed only sixteen intersection approaches with lagging sequences. Data problems later pared this list to fourteen approaches. Fortunately, these fourteen approaches were fairly homogenous: nine approaches were at intersections between two-way and one-way streets. The other five approaches were at intersections where the left turn opposing the left turn with the lagging sequence was either prohibited (in three cases) or had an extremely light volume (in two cases) so they also looked like intersections with one-way

streets.

The available lagging sequence approaches were compared to the set of approaches with leading sequences which had similar characteristics. A list of all the signals on state highways in four of the six INDOT districts was compiled and maps were used to reveal the type of each intersection. Fifteen approaches to intersections between two-way and one-way streets with leading signals were identified and eventually used for comparison to the lagging sequence approaches.

The set of approaches with leading signals was very similar to the set of approaches with lagging signals in many ways. The leading set had seven members in Indianapolis, while the lagging set had nine. The leading set had three ramp terminals in suburban areas, while the lagging set had two. The approaches in both sets which were not at ramp terminals were in the downtown or older urban areas of towns or cities. The left turn and through volumes were well distributed for both sets of approaches. The distributions of approach speeds, volumes of pedestrians, and other characteristics were also very similar between the leading and lagging sets of approaches.

Data Collection

Accident Data

Accident data from police records for the years 1985 through 1988 were used to make comparisons between the leading and lagging sequence sets of approaches. Those particular years were used for several reasons:

1. Several years of data were needed to obtain a potentially meaningful number of accidents.

2. The data were available from INDOT at the time of the project in a readilv usable form.

3. Each past year from which data are used generally increases the likelihood of significant changes in signal or other conditions in members of the sets of study approaches. Intersections were eliminated from the data set for such changes during 1985-1988, and using other years would have meant the elimination of more intersections. The year 1985 was chosen as the cut-off year that minimized this problem while at the same time satisfying item "one" above.

The use of three to five years of data in an accident study is a widely accepted standard in traffic engineering. Based on dated timing plans obtained for most intersections in the sample, dated maps showing the intersections in the sample, dated volume counts checked against recent counts, and the collective memories of the INDOT and city engineers, no significant permanent signal or other conditions changed at the approaches included in the comparison during the years 1985 through 1988.

A hard-copy listing of each police-reported accident which occurred near an intersection of interest was received from INDOT. The time, location, weather conditions, vehicles involved, drivers involved, and other aspects of each accident were included in the listing. The listings were manually examined to identify accidents of interest for this project, namely, accidents:

- involving vehicles turning left,

- on an approach with a left turn signal phase,

- which occurred at or within 100 feet of the intersections.

The data were also cross-checked for duplicate listing of the same accident. This occurred, for instance, where U.S. Route 33 in the City of South Bend was configured as a one-way pair and both of the one-way streets intersected Sample Street. Since there were two intersections in the city which fit the description "U.S. Route 33 and Sample Street," accidents coded as such were listed twice. All duplicate listing problems in the data sets were resolved except for five left turn accidents for which it was impossible to determine the true accident location between two contending intersections. Fortunately, both contending intersections had leading sequences, so the five accidents were arbitrarily assigned to one intersection and the group totals and means computed for the sets of approaches were not affected.

Traffic Volume Data

Traffic volume data for computing exposure over the four-year data collection period came from four sources. First, field observations were made at 13 of the 29 approaches in the leading and lagging sequence sets using manual counts conducted for this project. Three to four-hour turning counts were made which included at least one hour in one of the peak periods. Second, seven to eight-hour turning counts made for this project as part of the traffic conflict study (Chapter 4) provided many of the data needed for six approaches. Third, INDOT turning movement counts (mostly twelve hours long) conducted previously for other purposes were obtained for 11 approaches. Finally, the City of Indianapolis provided turning movement counts conducted previously for two approaches. The counts from the various sources were

expanded from several hours to four years using the appropriate adjustment factors from INDOT. Since the volume data were gathered from diverse sources over a wide range of time (two volume counts used were from November 1980, though most other volume counts used were recent), checks were conducted for the approaches with information from more than one source to insure the accuracy of the counting and expansion methods used. Table 18, containing a summary of the data checks, shows that volume data from different times and different sources matched very well.

Results

Accident Rates

Left turn accidents per million left turn vehicles and per million total vehicles entering the intersection are shown for approaches of interest in Table 19. Means and totals for the sets of lagging sequence and leading sequence intersections were computed and are also shown in Table 19.

Table 19 indicates that accidents were more frequent and occurred at a greater rate at intersections with leading sequences, though the difference between leading and lagging for either rate computed was not large. The mean rate of left turn accidents per million left turn vehicles was 0.9 for leading intersections and 0.8 for lagging intersections. The difference in rates between the two sets was not significant at the 0.05 level using the Z-test for proportions (Z = 0.83). The mean rate of left turn accidents per million total vehicles was 0.09 for leading intersections and 0.06 for lagging intersections. This difference was significant at the 0.05 level (Z = 2.54).

Besides the fact that the difference in accident rates between leading

Table 18. Checks on volume data from different times and sources.

Intersection	Description of Count 1	Description of Count 2	Estimated left turns in 0600-1800 time period	
			Count 1	Count 2
Washington and Delaware, Indianapolis	InDOT 12-hour count May 1986	Conflict study 7.5-hour count September 1988 converted to May 1986	2640	2580
Meridian and 12th, Indianapolis	InDOT six-hour count May 1981 converted to May 1989	Conflict study 7.5-hour count September 1988 converted to May 1989	1400	1640
Washington and Capitol, Indianapolis	InDOT 1.5-hour count November 1980 converted to May 1989	Project four-hour count May 1989	1950 (Total volume 34,900)	2000 (Total volume 31,800)
86th and SB Keystone ramp, Indianapolis	City of Indianapolis six-hour count September 1987 converted to May 1989	Conflict study eight-hour count September 1988 converted to May 1989	1780	1900

Table 19. Lead and lag set accident data summary.

Signal seq.	City	Intersection	Left turn accs.	Vol.,millions		Accs. per mil. vehs.	
				Left	Total	Left	Total
Lag	Indiana-polis	Meridian @ 12th	1	3.4	58	0.3	.02
		16th @ Pennsylvania	1	1.5	38	0.7	.03
		16th @ Capitol	1	2.7	68	0.4	.01
		Washington @ Illinois	2	5.1	86	0.4	.02
		Washington @ Capitol	8	4.0	72	2.0	.11
		Washington @ Penn.	3	4.3	56	0.7	.05
		Washington @ Delaware	4	6.0	92	0.7	.04
		Lafayette @ I-65 NB Ramp	3	5.2	39	0.6	.08
		86th @ Keystone SB Ramp	3	3.9	51	0.8	.06
Lead	Indiana-polis	Ohio @ Delaware	2	2.8	54	0.7	.04
		Market @ Delaware	3	3.2	51	0.9	.06
		South @ Delaware	1	3.2	46	0.3	.02
		South @ Pennsylvania	2	3.0	47	0.7	.04
		86th @ Keystone NB Ramp	4	3.1	no data	1.3	no data
		86th @ I-465 SB Ramp	6	13.9	27	0.4	.22
		71st @ I-465 SB Ramp	3	12.9	22	0.2	.14
Lag	Jasper	NB Newton @ 6th	8	3.6	35	2.2	.23
		EB 6th @ Newton	3	5.5	35	0.5	.09
	Princeton	Broadway @ Main	2	2.0	28	1.0	.07
		NB Main @ State	0	1.5	17	0.0	.00
	S. Bend	SB Portage @ Angela	5	6.9	43	0.7	.12
Lead	South Bend	Colfax @ Main	4	6.5	51	0.6	.08
		LaSalle @ Main	5*	5.8	71	0.9	.07
		LaSalle@ Michigan	12	2.7	58	4.4	.21
		Sample @ Main	6	4.1	54	1.4	.11
		Sample @ Michigan	15	1.7	61	9.0	.25
	Muncie	Madison @ Main	0	2.8	41	0.0	.00
		Madison @ Jackson	0	1.1	38	0.0	.00
	T. Haute	3rd @ Cherry	6	7.5	72	0.8	.08
Mean/Total All Lag Approaches			44	55.6	718	0.8	.06
Mean/Total All Lead Approaches			69	74.3	693	0.9	.09

* Accidents were assigned arbitrarily here; they could have happened at LaSalle @ Main.

and lagging intersections in Table 19 was quite small, there are at least three other reasons that extreme caution should be exercised before making left turn signal sequence policy decisions based on that accident experience. First, accident rates based on small samples of intersections are generally very volstile, and these sets are no exception. For example, the difference in accidents between the sets of leading and lagging sequence intersections in Table 19 was probably because of two intersections in the city of South Bend which together accounted for 27 accidents—almost 40 percent of the total from all 15 leading intersections. Second, any of a number of possible biases may account for some or all of the difference between leading and lagging observed. The comparison in Table 19 was controlled for signal type and general intersection configuration, and the data were normalized with traffic volumes, but many factors were not controlled. Finally, the difference seen in Table 19 may not hold for other intersection configurations and signal types.

Another general conclusion that could be drawn from Table 19 is that the number of left turn accidents which occurred per intersection per year was relatively low regardless of the signal sequence. One-hundred and thirteen left turn accidents were recorded at 29 intersection approaches over four years, for a rate of just under one accident per approach per year. This conclusion has a much higher likelihood of being generally true than the conclusion discussed earlier regarding the difference between leading and lagging sequences because of a higher sample size and fewer uncontrolled factors. One of the consequences of the relatively low number of accidents per approach per year is that a large sample of intersections would be necessary in any future extensive evaluation of leading and lagging sequences or other left turn

alternatives using accidents. In addition, modest changes in the overall traffic safety picture of a region are all that can be expected from even the most widespread left turn safety treatment programs if the number of accidents occurring before the programs begin is low.

Accident rates were also computed for four approaches which were of interest during this research but which did not belong in the comparison discussed above. The north-bound and southbound approaches to the intersection of Markland and Washington in the City of Kokomo were found to be the only protected-lagging signals in Indiana. The northbound approach witnessed three left turn accidents from 1985 through 1988 with a left turn volume of 2.5 million vehicles (a rate of 1.2 accidents per million left-turning vehicles) and with a total intersection volume of 45 million entering vehicles (a rate of 0.07 accidents per million entering vehicles). The southbound approach had 12 left turn accidents with a left turn volume of 4.6 million vehicles (for rates of 2.6 accidents per million left-turning vehicles and 0.27 accidents per million total vehicles). The fact that these rates were above the means shown in Table 19 for lagging sequences is probably due to the sizeable offset of the northbound and southbound legs of this intersection rather than the signal sequence or type.

The southbound approach of Main at State in the City of Princeton and the northbound approach of Portage at Angela in the City of South Bend were also of interest for this research because they were the only known approaches in Indiana where the conditions for trapping were present. In each case, a permissive left turn signal was provided while the opposite approach had a permissive-protected signal. The INDOT accident records indicated that none of the permissive approaches had experienced a left turn accident from 1985 to

1988. This finding does not mean that trapping potential should be ignored. Rather, the finding indicated only that trapping may not be as serious as first considered at a certain type of intersection. In particular, both left turn volumes of interest were very low in comparison to the volumes at the intersections on Table 19 (approximately 0.3 million left-turning vehicles in the four-year period from southbound Main at State and 0.5 million from northbound Portage at Angela). In addition, the street onto which the vehicles were turning was in each case a short local street, and drivers who repeatedly use an intersection are likely to quickly learn the peculiarities of the signal. Thus, the lack of accidents at the two sites indicated only that trapping may not be a serious problem at long-established signals serving turns with low volumes onto local streets.

Accident Details

The variation of left turn accident rates with traffic volume at the intersections in the lead and lag comparison sets (i.e., the intersections in Table 19) was investigated. Table 20 shows the accident rates varying with the volume of left-turning vehicles, and Table 21 shows the accident rates varying with the volume of total vehicles. The tables show that there was no clear trend in the relationship between volume and the associated accident rate. The tables also illustrate that the lead and lag sets had similar distributions of traffic volumes.

The severity of left turn accidents at the intersections in the lead and lag comparison sets was also examined. Of the 69 accidents at leading sequence intersections, 25 (35 percent) caused one or more reported personal injuries. In contrast, only three of the 44 accidents at lagging sequence intersections

Table 20. Mean accident rates by left turn volume class.

Left turn volume class, millions	Number of intersections		Mean accidents per million left turn vehicles	
	Lag	Lead	Lag	Lead
1.0-1.9	2	2	0.3	5.4
2.0-2.9	2	3	0.4	1.6
3.0-3.9	3	4	1.2	0.8
4.0-5.9	5	2	0.8	1.1
6.0-7.9	2	2	0.7	0.7
12.0-13.9	0	2	no data	0.3

Table 21. Mean accident rates by total volume class.

Total volume class, millions	Number of intersections		Mean accidents per million total vehicles	
	Lag	Lead	Lag	Lead
Under 30	2	2	0.02	0.18
30-49	5	4	0.11	0.02
50-59	3	5	0.05	0.10
60-79	2	3	0.06	0.13
80 and over	2	0	0.03	no data

(seven percent) caused one or more injuries. A chi-square test on these data showed that the signal sequence was significantly related to the proportion of injury to total accidents at the 0.05 level. This difference was also independent of the effects of the relatively high-accident leading sequence intersections in the City of South Bend mentioned earlier. Only nine of the 25 leading sequence injury accidents happened at the two relatively high-accident South Bend intersections, and injury accidents at the leading sequence intersections excluding all five South Bend sites still made up 41 percent (11 of 27) of all left turn accidents. Left turn accidents at intersections with leading sequences were clearly much more severe in this data set than similar types of accidents at intersections with lagging signals.

Table 22 shows the breakdown of the accidents in the lead and lag comparison sets by light and pavement conditions at the time of the accident. A chi-square test on these data showed that there was no significant relationship between the signal sequence and the pavement and light conditions at the time of the accidents in the sample. Thus, these factors did not help account for the differences in rates or severity noted in the discussions above.

The type of collision was also examined for the accidents in the lead and lag comparison sets to see whether some of the differences in rates and severity could be explained. Table 23 provides a breakdown of the coded collision type for each accident between the lead and lag intersections. Like the data for light and pavement conditions, these data did not help account for the differences between lead and lag. The proportions of accidents of the types most likely related to the left turn signal (i.e., left and opposite and rear-end accidents) to all left turn accidents were 0.84 for the lead intersections and 0.75 for the lag intersections. A chi-square test on the data

Table 22. Accidents in the lead and lag comparison sets by pavement and light condition at the time of the accident.

Coded pavement condition	Coded light condition	Lagging sequence intersection set		Leading sequence intersection set	
		Number of accidents	Percent of lagging total	Number of accidents	Percent of leading total
Dry	Day	29	66	44	64
Dry	Other than day	8	18	10	14
Other than dry	Day	3	7	10	14
Other than dry	Other than day	4	9	5	7
Total, all conditions		44	100	69	100

Table 23. Accidents in the lead and lag comparison sets by coded collision type.

Coded collision type	Lagging sequence intersection set		Leading sequence intersection set	
	Number of accidents	Percent of lagging total	Number of accidents	Percent of leading total
Left turn and opposing vehicles involved	30	70	50	75
Same direction, same lane (i.e., rear-end)	2	5	6	9
Same direction, different lanes (i.e., sideswipe)	9	21	5	7
Left turn vehicle and vehicle on intersecting street	2	5	6	9
Total, all types	43*	100	67*	100

* Does not include two leading and one lagging sequence accidents which were coded as collision type "unknown."

(using two categories of collision type: left and opposite plus rear-end accidents and other accidents) revealed no significant relationship between collision type and signal sequence at the 0.05 level.

Chapter Summary

Accident data were used to help gain a better understanding of the relative safety of leading and lagging sequences. Rates of left turn accidents per million left-turning vehicles and left turn accidents per million total entering vehicles were computed for the years 1985 through 1988 for all known lagging sequence sites in Indiana and for the set of similar types of leading sequence sites. The major finding of the accident analysis involved a comparison of the rates between the lead and lag intersections. Little difference between the leading and lagging sets was observed for left turn accidents per left turn vehicle. However, the lagging sequence set had significantly smaller rates of left turn accidents per entering vehicle. A comparison of the severity of these accidents showed that accidents at the leading sites were significantly more likely to result in at least one reported personal injury. The light and pavement conditions at the time of the accidents in question and the collision types did not account for the difference in rates or severity. Because the sets of intersections were relatively small and many factors were not controlled in the comparison of lead and lag, however, extreme caution was advised in the use of these results.

CHAPTER 6 - SIMULATIONS

Introduction

Chapters 4 and 5 addressed the relationship of safety to left turn signal sequence. In this chapter, safety was also addressed, particularly in the discussion below on the utilization of signal phases by left turning vehicles. However, the emphasis in this chapter was shifted to delay, which is the other important measure of effectiveness related to the lead and lag issue.

Delay was investigated through the use of the NETSIM simulation model of traffic flow. The use of simulation allowed experiments to be set up with control over many factors which would not have been possible in field experiments. Simulation also allowed many more data to be collected than would have been feasible in the field.

NETSIM was chosen for this research for several reasons. NETSIM is a well-established model supported by the Federal Highway Administration (FHWA). NETSIM is microscopic (i.e., modelled the behavior of individual vehicles) and stochastic, which mean increased accuracy over macroscopic models and the ability to perform analyses such as the utilization of signal phases experiment. NETSIM was chosen over another available microscopic model, the TEXAS model [Lee et al. 1985], because it simulated an entire network of arterial streets rather than just one intersection. This feature was crucial because the literature review revealed the importance of progression along arterials to the lead and lag issue and because various states of progression can be modelled with NETSIM using signals upstream of the signal of interest. The major drawback of the use of NETSIM, that vehicles are input to the simulated network at uniform rates, was mitigated by introducing signals upstream.

Five separate experiments were run using data from NETSIM. The study of the utilization of the various signal phases was one experiment. Another experiment was conducted using actual intersection data as inputs. The other three experiments included simulations of an intersection with four approaches, an intersection with three approaches, and a diamond interchange with both ramp terminals signalized. These latter three experiments were conducted for two reasons. First, the intersection configurations tested were those for which the lead and lag issue was relevant. Second, the configurations tested were common in Indiana.

Model

The June 1986 microcomputer version of NETSIM was used in the study. Input for the model was coded according to the NETSIM user's manual [FHWA 1980]. A NETSIM "run" consisted of thirty minutes (in most cases) of continuous simulated traffic flow under constant conditions after a warm-up period during which the number of vehicles in the network stabilized. An experiment consisted of many different runs, each of which had one or more set-up conditions different from other runs. The measures of effectiveness (MOE's) recorded for analysis were read from the standard final output from a NETSIM run, a sample of which is shown in Figure 7.

NETSIM requires users to completely specify almost every facet of the streets and signals being modelled. The intent in building models with NETSIM during this research was to provide a fair test of leading and lagging sequences at intersections which were representative of those in Indiana where the choice of a left turn signal sequence was potentially important. Many parameters for NETSIM were determined on the basis of the results from a ran-

LINK STATISTICS

Link	Veh- miles	Veh trp	Mov. time v-min	Delay time v-min	M/T	Total time v-min	T-time /veh sec	T-time/ veh-mile sec/mile	D-time /veh sec	D-time/ veh-mile sec/mile	Pct stop delay	Avg. speed mph	Avg. occ.	Stops /veh	Avg sat pct	Cycl fail
(62,61)	107.5	215	212.5	95.9	.69	308.4	86.1	172.1	26.8	53.0	64	20.9	10.2	.71	8	0
(64,61)	104.5	209	215.8	83.6	.72	299.4	85.9	171.9	24.0	48.0	59	20.9	9.9	.68	7	0
(85,61)	80.5	322	99.6	52.8	.65	152.5	28.4	113.6	09.8	39.4	62	31.7	5.1	.42	4	0
(65,85)	81.8	327	100.6	45.7	.69	146.2	26.8	107.3	08.4	33.5	00	33.5	4.8	.01	4	0
(83,61)	80.5	322	100.3	55.9	.64	156.2	29.1	116.4	10.4	41.7	59	30.9	5.2	.39	4	0
(63,83)	81.5	326	101.5	45.8	.69	147.2	27.1	108.4	08.4	33.7	00	33.2	4.9	.01	4	0

Figure 7. Sample NETSIM output.

dom sampling of intersections which have some form of left turn signalization and are located in four of the six INDOT districts. Other parameters were determined in consultation with the technical advisors for the project or with INDOT and Indianapolis Department of Transportation personnel.

The number of factors which were varied in each experiment was limited. Factors which were not expected to affect the choice of left turn signal sequence, did not vary much in the intersections sampled, could not be varied with NETSIM, or were not available routinely to traffic engineers using the results from this research to establish signal phasing plans were kept constant in all experiments. Such factors included the:

- percent trucks in the traffic stream (six),
- phase split between major and minor approaches to a signal (60/40),
- approach grades (nil),
- number of through lanes on a major street (two in each direction),
- median width (nil), and
- angle of intersections (90 degrees).

Within each experiment, inputs related to the minor street were also kept constant. The Signal Operations Analysis Package (SOAP) was used constantly throughout all experiments to produce left turn phase splits for fixed-time and coordinated actuated signals [FHWA 1985].

NETSIM contained many so-called imbedded parameters which described minute details of vehicle behavior. Most of the default values for these parameters were used throughout the simulations. However, two imbedded parameters were investigated using field data during this project because it was suspected that the default values in NETSIM (based on mid-1970's drivers in Washington, D. C.) may not be representative of Indiana drivers in 1989, because the parameters were measurable with limited resources in the field, and because the parameters may be particularly important during a study of vehicle delay and left turn signals. The first parameter investigated was the lost time experienced by the first vehicle in a queue when a signal turned green. Lost time was measured with a stop watch for fifty randomly selected queue leaders in the through lanes of an approach with a leading left turn signal (South at Delaware in Indianapolis) and fifty similar vehicles at an approach with a lagging signal (Meridian at 12th in Indianapolis). The mean lost time for each sample was 2.3 seconds, which was almost identical to the mean of the distribution of lost time imbedded in NETSIM. A Z-test revealed that there was no statistically significant difference between the means for the leading and lagging signals. Thus, the default lost time distribution in NETSIM was used throughout the simulations.

The second imbedded parameter tested with field data was the acceptance of gaps in oncoming traffic by left turning vehicles. The intersections of Kentucky at Raymond and Emerson at Raymond in Indianapolis were selected for field data collection because they had moderate left turn and through volumes (with reasonable distributions of available gap sizes), permissive signals, two through lanes, and moderate approach speeds of 35 to 45 miles per hour. The data from several hours of observation at each intersection using a stop

watch and tape recorder in dry weather are provided in Table 24. The gap accepted by fifty percent of drivers was about 5.1 seconds at the sample intersections, as compared to 4.6 seconds for the default NETSIM distribution. Because the field data differed consistently from the NETSIM default distribution, a decile distribution based on the data from Table 24 was created and used throughout the simulation experiments. Table 25 shows this new distribution along with the discarded NETSIM default distribution.

Validation

There are several reasons that suggested that NETSIM could be used in this research without a lengthy model validation process. First, NETSIM has been used to study various traffic control schemes by many researchers [Smith 1983, Davis et al. 1987, Hagerty and Maleck 1981, and Yauch et al. 1988]. Second, the acceptance of NETSIM as an accurate representation of the real world is such that NETSIM is often used to check the accuracy of other, less sophisticated, models of traffic flow [Cohen and Mekemson 1985 and Nemeth and Mekemson 1983]. Third, only minor changes were necessary to the imbedded parameters of NETSIM during the simulation experiments, as noted above, and no changes were needed to the underlying logic of the model. Finally, the methods available to obtain the comparable data in the field were crude and perhaps unreliable themselves.

Another reason that an extensive validation of the NETSIM model was not necessary was the availability of recent data which compared NETSIM models very similar to those used in these experiments to field data and indicated that the models were valid. During a study in New Jersey using NETSIM to establish warrants for left turn signalization [Smith 1983], the total travel

Table 24. Gap acceptance data collected for this research at two Indianapolis intersections.

Gap size, seconds	Number of vehicles viewing gap	Number of vehicles accepting gap	Percent of vehicles accepting gap
2.0-2.9	173	3	2
3.0-3.9	146	9	6
4.0-4.9	126	31	25
5.0-5.9	81	47	58
6.0-6.9	64	44	69
7.0-7.9	37	28	76
8.0-8.9	41	40	98
9.0-9.0	29	26	90

Table 25. Imbedded NETSIM and new gap acceptance distributions.

Percent of drivers who would accept the given gap or any larger gap (i.e., the decile distribution)	Imbedded NETSIM gap size, seconds	New project data gap size, seconds
10	2.7	3.3
20	3.6	3.9
30	3.9	4.5
40	4.2	4.8
50	4.5	5.1
60	4.8	5.4
70	5.4	6.1
80	6.0	7.4
90	6.6	7.9
100	7.8	8.4

time in seconds per vehicle was compared for nine approaches for NETSIM and field data collected with a video camera. Table 26, with those data, shows that the NETSIM models underestimated travel time relative to field data but generally did a reliable job. Statistical tests conducted on the data in Table 26 by the researchers in New Jersey showed that there was no difference at the 0.05 level between the simulated and field estimates of total time per vehicle.

Other data validating NETSIM were generated during a recent experiment on detector placement for actuated signals conducted at Purdue University with the same version of NETSIM and very similar inputs as this research [Davis et al. 1987]. The estimates of delay and vehicle speed produced with NETSIM were compared to field estimates for four approaches to one signal in Indianapolis. Table 27 shows that the field and NETSIM estimates matched reasonably well indicating that NETSIM is a reasonable analysis tool for the simulation of traffic flows.

To strengthen the case that NETSIM was a valid model of traffic flow for this research, data were collected in the present study over several 15-minute periods at the intersection of Ohio and Delaware in Indianapolis and the intersection of 18th and Salem in Lafayette, Indiana. These data were then compared to data generated with NETSIM models of the same intersection conditions. Both intersections had protected-permissive signals. It was not possible during the period of the study to collect data for validating NETSIM at an intersection with a lagging sequence due to construction and other problems. The characteristics of the intersection at Ohio and Delaware mentioned earlier in Chapter 4 are summarized along with the characteristics of the intersection at 18th and Salem in Table 28.

Table 26. NETSIM validation data from New Jersey study [Smith et al. 1983].

Approach	Total time, seconds per vehicle		Difference* between field and NETSIM, seconds
	Field data	NETSIM data	
Route 206 @ Route 518	20.1	14.1	6.0
Scotch @ Route 546	38.0	35.0	3.0
Route 29 @ Upper Ferry	13.2	11.7	1.5
Delaware @ Route 31	43.4	39.0	4.4
Route 31 @ Delaware	20.5	22.0	-1.5
Prospect @ Olden	37.0	32.4	4.6
South Broad @ Trebor	9.2	12.3	-3.1
Trebor @ South Broad	63.6	50.7	12.9
Harrison @ Hamilton	13.2	20.2	-7.0

* The mean difference for all approaches was 2.3 seconds and the standard deviation was 5.8 seconds

Table 27. NETSIM validation data from recent Purdue University study [Davis et al. 1987].

Approach to Girls School and 10th intersection, Indianapolis, IN	Delay time, seconds per vehicle		Difference between field and NETSIM, seconds
	Field data	NETSIM data	
Northbound	32.0	46.8	-14.8
Eastbound	33.8	37.6	-3.8
Southbound	41.7	51.3	-9.6
Westbound	31.4	36.2	-4.8

Table 28. Characteristics of intersections where validation data were collected.

Characteristic	Ohio @ Delaware	18th @ Salem
City	Indianapolis	Lafayette, IN
Area	Downtown	Urban
Pedestrians	Almost every cycle	Few
Number of approaches	3	3
Distance to other member of one-way pair, feet	528	330
Time for leading left turn arrow, sec.	10	7
Time for yellow left turn arrow, sec.	4	3*
Time for green ball, seconds	22	30
Time for yellow ball, seconds	4	3
Cycle length, seconds	70	70
Number of through approach lanes	2	1
Left turn lane	No	Yes
Right turn lane	No	No
Right turn on red	No	Yes
Posted speed limit, mph	25	35
Left-turn signal arrangement	Five-head doghouse	Four-head stacked

* There was no yellow arrow but three seconds elapsed every cycle between the time the green arrow turned off and the time the opposing green ball turned on.

The types of field data collected included the stopped delay and the number of stops experienced by vehicles on an approach with a left turn arrow and the number of vehicles which turned left on the green arrow. These measures were important during the simulation experiments and could be obtained in the field using standard techniques. Two observers recorded field data. One observer recorded the number of left turns on the green arrow and other left turn phases and the number of vehicles stopped on the approach of interest every 13 seconds. These latter data were then converted into an estimate of stopped delay [Hostetter and Lunenfeld 1982]. The second observer recorded volume counts for each movement on the major street and the number of stops made by vehicles on the approach of interest. Problems with some of the "number of left turns on the green arrow" and the "number of stops" data, however, meant that those data were compared with simulation data at only one intersection each.

The simulations used for comparison to the field data had most of the same characteristics as the simulation models used in the experiments described later in this chapter. The major difference between these validation runs and later experiment runs was that the time period being simulated was 15 instead of 30 minutes. Ten simulation runs were made for each 15-minute period of field data available, with only the random number seed varying between runs.

A summary of the field and simulation data generated for comparison is given in Table 29 for the intersection of Ohio and Delaware. The field estimate for stopped delay was within a 95-percent confidence interval for the mean of the simulation runs for one of the four time periods, was higher than the confidence interval bounds for one time period, and was lower than the

Table 29. Ohio at Delaware intersection validation results.

Measure	Statistic	15-minute data collection time period			
		1150-1205	1205-1220	1220-1235	1235-1250
Stopped delay for all vehicles on approach, minutes	Field data	10.6	11.3	10.8	15.0
	Mean, NETSIM runs	10.1	13.5	14.3	12.9
	Standard deviation, NETSIM runs	1.8	2.1	1.4	1.5
	Low conf. int. bound NETSIM runs	8.8	12.0	13.3	11.8
	High conf. int. bound NETSIM runs	11.4	15.0	15.3	14.0
	Low result, NETSIM runs	7.9	9.0	12.3	10.7
	High result, NETSIM runs	13.0	16.8	17.1	15.2
Number of left turns completed during green arrow phase	Field data	8	6	6	3
	Mean, NETSIM runs	14.9	8.9	8.6	7.4
	Standard deviation, NETSIM runs	4.5	4.0	4.3	3.0
	Low conf. int. bound NETSIM runs	10.7	6.0	5.5	5.2
	High conf. int. bound NETSIM runs	18.1	11.8	11.7	9.6
	Low result, NETSIM runs	8	1	1	2
	High result, NETSIM runs	21	14	15	12

interval bounds for the other two time periods. The field estimates of the number of left turns completed on the green arrow indication were consistently lower than the simulation estimates, but were still not unreasonably different. In two cases, a 95-percent confidence interval constructed from the ten simulated data points contained the value of the field estimate. It was also observed that the simulation mean and the field estimate for the percent of left turns on the green arrow indication rose and fell together for the four time periods studied.

Table 30 presents field and simulation results for the intersection of 18th and Salem. The field estimates of stopped delay were reasonably close to the means of the simulated runs, although the simulation means were consistently lower. For one of the seven time periods, the 95 percent confidence interval for the mean of the simulation runs contained the value of the field estimate. For the other six time periods, the confidence intervals for the simulation runs were lower than the field estimates. The number of stops data illustrated the same pattern. For five of the seven time periods the field estimate was higher than the confidence interval on the mean of the simulation runs. For two time periods, the confidence interval on the mean of the simulation runs contained the value of the field estimate.

Since the true value of any measure analyzed during this validation study was unknown, it was not certain whether NETSIM was slightly underestimating or the field data collection slightly overestimating the measures of interest. It was clear, though, that NETSIM produced results relatively close to the field estimates and that the simulation and field results varied consistently from case to case.

Table 30. Eighteenth at Salem intersection validation results.

Measure	Statistic	15-minute data collection time period						
		0300-0315	0315-0330	0345-0400	0400-0415	0415-0430	0430-0445	0445-0500
Stopped delay for all vehicles on approach, minutes	Field data	22.3	24.1	31.2	37.9	25.4	35.5	32.2
	Mean, NETSIM runs	19.9	20.8	26.5	31.2	23.6	27.7	25.0
	Standard deviation, NETSIM runs	2.6	1.9	3.2	2.5	2.7	2.8	2.1
	Low conf. int. bound NETSIM runs	18.0	19.4	24.2	29.4	21.7	25.7	23.5
	High conf. int. bound NETSIM runs	20.8	22.2	28.8	33.0	25.5	29.7	26.5
	Low result, NETSIM runs	15.4	17.8	20.4	26.1	20.1	25.0	22.1
	High result, NETSIM runs	23.5	24.0	31.3	35.3	27.5	33.8	30.1
Number of stops for all vehicles on approach	Field data	82	84	124	140	118	132	135
	Mean, NETSIM runs	86.1	87.2	114.3	127.9	101.2	112.6	103.2
	Standard deviation, NETSIM runs	8.2	6.6	10.2	8.6	7.1	9.3	7.4
	Low conf. int. bound NETSIM runs	74.6	82.5	107.0	121.7	96.1	105.9	97.9
	High conf. int. bound NETSIM runs	97.6	91.9	121.6	134.1	106.3	119.3	108.5
	Low result, NETSIM runs	74	78	99	109	92	96	94
	High result, NETSIM runs	102	102	131	136	116	128	120

Intersections with Four Approaches

Experiment Set-Up

Intersections with four approaches are the most common type of intersections with left turn phasing in Indiana and were therefore afforded the most attention among the simulation experiments. The factors and levels examined during this experiment included:

- desired approach speed (SP): 30 and 50 miles per hour (mph);
- signal type (FA): fixed-time and actuated;
- progression class (P): none, one direction "perfect," both directions "perfect," and "early;"
- left turn volume (L): 140 and 230 vehicles per hour (vph);
- through volume (T): 600 and 1000 vph; and
- left turn signal type (S): permissive, protected-permissive, permissive-protected, protected-leading, and protected-lagging.

These factors were varied only on the major street of interest.

The terms used above for the progression variable require explanation. "No" progression means that adjacent signals along the major street were one-half of a mile distant and operated with different cycle lengths than the signal of interest. "Perfect" progression refers to the condition in which the

leading edge of the through band travelling at the desired approach speed arrived at the intersection of interest exactly as the green ball signal was displayed. It should be noted that "perfect" progression does not necessarily mean that delay is minimized on the major street. "Early" progression was suggested by the INDOT study technical advisor as a much more typical type of progression than perfect or none. With early progression, the leading edge of the through band in one direction on the major street travelling at the desired approach speed arrived at the intersection before the green ball signal by an amount of time equal to three-fourths of the green ball signal duration. Meanwhile, the leading edge in the other direction arrived early by an amount of time equal to one-fourth of the green ball signal duration. Thus, for a green ball duration of 28 seconds, the early progression class had the through band arriving 21 seconds before the appearance of the green ball in one direction and seven seconds before in the opposite direction.

The left turn and through volume levels used in this experiment and throughout the study were based on random samples of intersections with left turn signals on Indiana state highways. The levels represent approximately the mean and the mean plus one standard deviation of the volume levels experienced at intersections in the sample of interest during weekday peak hours. The combination of the high left turn and high through volume levels with protected signal schemes led to nearly saturated conditions, but all other combinations of volume and signal levels led to unsaturated conditions. The relatively low levels of traffic volume used must be considered when the results from this study are applied.

The network of streets and intersections simulated in this experiment is shown schematically in Figure 8. Data were analyzed only for the two major

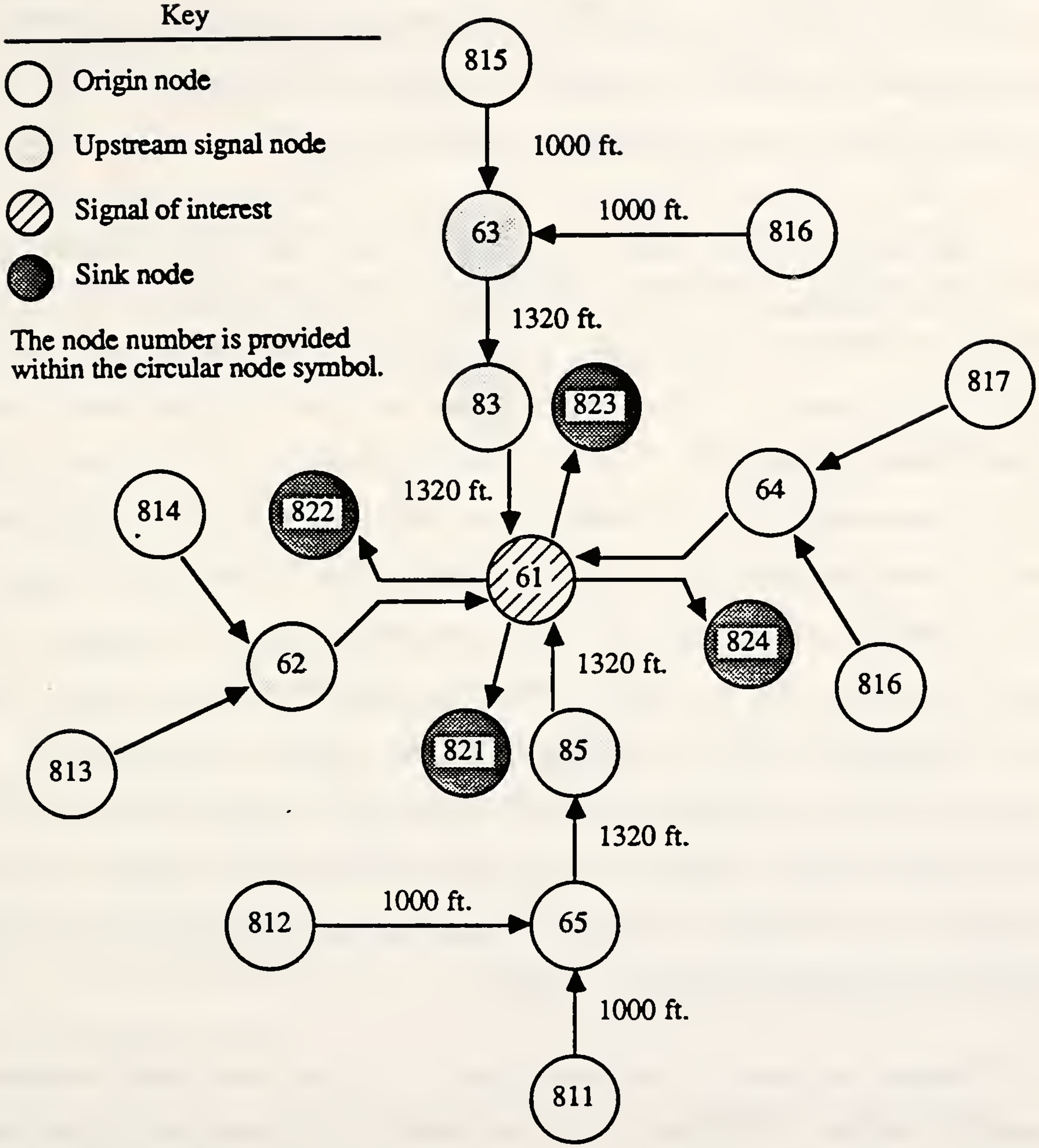


Figure 8. NETSIM nodes and links for intersection with four approaches.

street approaches to node 61 (i.e., links 83,61 and 85,61). Eighty percent of the traffic destined for node 61 from node 85 was generated at node 811, while the remainder originated from node 812. Likewise, 80 percent of the traffic for node 61 from node 83 originated at node 815.

Signal timing parameters representative of practices in Indiana were used for the various combinations of factors in this experiment. One limitation imposed by NETSIM was that signal timing parameters had to be input in whole second increments, whereas the standard practice in Indiana was to provide signal timing parameters in terms of percent of the cycle. In terms of signal timing parameters, it is important to note that leading and lagging phases were treated identically for a given combination of other factors except for the signal sequence and the offsets for the progression variable. An 80-second cycle was used at fixed-time and coordinated actuated signals during this experiment, with a one-second all-red interval between phases. Four-second yellow intervals were used when the approach speed was 50 mph, while three-second yellow intervals were employed with 30-mph approach speeds. A minimum left turn green arrow time of seven seconds was established during the SOAP runs to optimize the phase lengths.

Detector placement at actuated signals in the experiment depended on several factors. Thirty-six-foot long presence detectors were placed immediately behind the stop bar in left turn lanes of the major street and all lanes of the minor street with all forms of actuated signals. With 30-mph approach speeds at isolated actuated signals (i.e., progression class of "none"), these detectors were supplemented by 36-foot long presence detectors in the through lanes of the major street. All presence detectors were associated with a five-second constant initial interval and a two-second passage time. With

50-mph approach speeds at actuated isolated signals, the presence detectors were supplemented by six-foot long counter detectors placed 365 feet behind the stop bar in the through lanes of the major street. The counter detectors were associated with a 15-second minimum initial interval, 20 actuations before time was added to the initial interval, a six-second passage time, a four-second minimum gap, and thirty seconds to reduce to the minimum gap. Maximum green ball phases for isolated signals were set at 45 seconds, while maximum left turn green arrow phases were set at 30 seconds.

At actuated coordinated signals, the non-actuated (major street green ball) phase was fixed in the 80-second cycle and was guaranteed to last as long as the same phase under the same conditions with fixed-time operation. A yield point was set at the end of the guaranteed green ball time. The end of the yield interval was placed such that two seven-second green phases (one phase in the permissive signal case) with accompanying yellow and all-red intervals were possible before the start of the guaranteed green ball phase. Force-offs were placed in the cycle to insure that if calls were issued the signal would give each non-guaranteed phase at least seven seconds of green ball time and to insure the return of control to the non-actuated green ball phase at the appropriate time.

Several other features of the simulation for this experiment should be noted. It was assumed that no pedestrians crossed streets at the intersections in the network. Right turn volumes were held constant at 110 vph. Right turns on red were allowed at node 61 for approaches with 50 mph approach speeds but were prohibited for approaches with 30 mph approach speeds. Left turn lanes with capacities of 15 vehicles were standard at node 61, but right turn lanes with capacities of nine vehicles were provided only at node 61 when

the approach speed was 50 mph.

An important limitation imposed by NETSIM during this experiment was the inability to model the five-phase operation of leading coordinated signals. Five-phase actuated signal operation is illustrated in Figure 9. Five-phase operation is a definite advantage for protected-permissive signals because the possibility of trapping prevents permissive-protected signals from using this operation. To keep the experiment consistent, five-phase operation was not used during the experiment runs of any isolated actuated signal. The extent of the bias introduced by this limitation was unknown but was probably not great in this experiment because equal traffic volumes in both directions on the main street were modelled and five-phase operation is most beneficial when traffic volumes are unbalanced.

A complete factorial experiment using the factors and levels listed above would have required 320 simulation runs. Since the preparation for each individual run was time consuming and since little was lost in the way of statistical accuracy, the experiment was run as a one-half fractional factorial and only 160 runs were made. The equation used to generate the list of combinations was [Anderson and McLean 1974]:

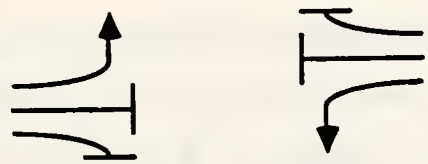
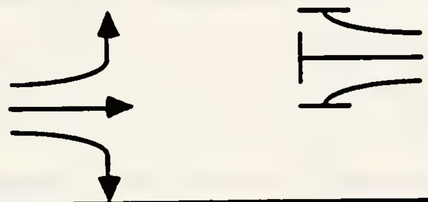
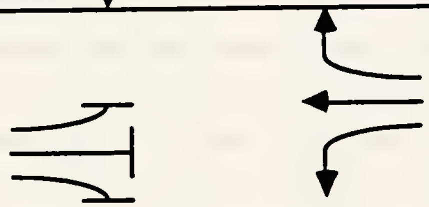
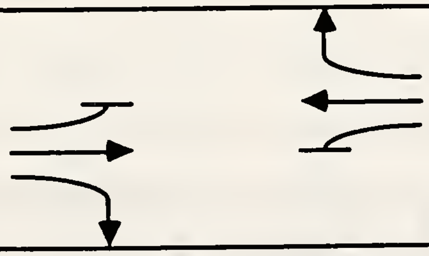
$$A = X1 + X2 + X3 + X4 + X5 + X6, \text{ modulus } 2 \tag{1}$$

where:

A = 0 if the combination was included in the experiment and 1 if the combination was not included in the experiment,

X1 = 0 for 50 mph and 1 for 30 mph,

X2 = 0 for fixed-time and 1 for actuated,

Phase	Main street movements allowed
1	
2	
3	
4	
5	Side street movements serviced

The controller may select phase 2, 3, or 4 after phase 1 is terminated.

Figure 9. Five-phase actuated protected signal control.

X3 and X4 = progression class (X3 = 0 and X4 = 0 for no progression, X3 = 1 and X4 = 0 for one direction perfect progression, X3 = 0 and X4 = 1 for early progression, and X3 = 1 and X4 = 1 for both directions perfect progression),

X5 = 0 for 140 and 1 for 230 vph, and

X6 = 0 for 600 and 1 for 1000 vph.

Use of Equation 1 above insured that no single factor or interaction between two factors was confounded with another single factor or two-factor interaction. Each of the 32 combinations designated for inclusion in the experiment was completely crossed with the left turn signal variable with five levels to produce the list of 160 necessary runs. Interactions with three or more factors were assumed to be negligible to provide an error term for the analysis of variance (ANOVA), which was the main statistical test used on the experiment data.

Results

A set of coded data for all 160 runs in this experiment is provided in Appendix A. From the raw data three MOE's were computed, including total delay in seconds per vehicle, stopped delay in seconds per vehicle, and the number of stops per vehicle. A mean value of each MOE weighted by the total number of vehicles on the two major street approaches to node 61 was used. Results with NETSIM were provided for all vehicles on a link regardless of their movements, so separate results for left-turning vehicles were not possible. SAS [SAS Institute, Inc. 1985] was used on the Purdue University Computing Center mainframe for statistical computations.

Table 31 shows the ANOVA results for total delay. All six factors were significantly related to delay at the 0.05 level. Several two-factor interac-

Table 31. ANOVA results for delay at the four-approach intersection.

Factor or interaction	Degrees of freedom	Sum of squares	F value	Significance probability
SP	1	223.6	71.5	0.0001
FA	1	422.8	135.1	0.0001
P	3	214.4	22.8	0.0001
L	1	356.5	114.0	0.0001
T	1	468.6	149.8	0.0001
S	4	1910.5	152.6	0.0001
SP*FA	1	11.9	3.8	0.0536
SP*P	3	28.3	3.0	0.0334
SP*L	1	0.7	0.2	0.6489
SP*T	1	0.0	0.0	0.9254
SP*S	4	17.5	1.4	0.2409
FA*P	3	102.0	10.9	0.0001
FA*L	1	0.4	0.1	0.7177
FA*T	1	5.4	1.8	0.1886
FA*S	4	30.4	2.4	0.0523
P*L	3	4.0	0.4	0.7372
P*T	3	22.1	2.4	0.0758
P*S	12	211.2	5.6	0.0001
L*T	1	6.1	2.0	0.1652
L*S	4	85.2	6.8	0.0001
T*S	4	60.7	4.8	0.0013
ERROR	102	319.2	----	-------
TOTAL	159	4182.5	----	-------

The notation "SP*FA," for example, means the interaction between the speed factor (SP) and the signal type factor (FA).

tions were also significant at the 0.05 level, including the interaction of progression class and left turn signal type (P*S) and the interaction of through volume level and left turn signal type (T*S). The mean values for delay for each level of each factor are given in Table 32. Higher speeds, actuated signals, early progression, lower left turn volumes, and lower through volumes all meant lower values for delay. For the left turn signal type (S), Table 32 shows that the ranking of signals from most delay to least was protected-leading, protected-lagging, protected-permissive, permissive-protected, and permissive. A Student-Newman-Keuls test of the means showed that all levels of S were significantly different from all other levels at the 0.05 level except for the protected-leading and the protected-lagging. The P*S interaction was significant primarily because protected-permissive and permissive-protected signals both caused less delay than permissive signals for early progression and more delay for other progression classes. One possible reason for the finding of less delay with early progression and protected-permissive and permissive-protected signals was that vehicles may have travelled primarily in the middle of or late stages of the through band rather than at the beginning. With early progression, such vehicles would be arriving at the intersection with the green ball signal. The T*S interaction was significant due to the relatively good performance of permissive-protected and protected-permissive signals with lower through volumes.

The ANOVA results for stopped delay are given in Table 33. Table 34 presents the means for stopped delay for each level of each factor. The results are very similar to the results for delay discussed above with three exceptions. First, the speed factor (SP) was not a significant factor in explaining the variation in stopped delay at the 0.05 level. Second, the

Table 32. Mean values of delay for main effects at the four-approach intersection.

Factor	Level	Number of observa-tions	Mean delay, seconds per vehicle	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
SP	30	80	16.9	----
	50	80	14.5	----
FA	fixed	80	17,3	----
	actuated	80	14.1	----
P	none	40	16.0	one perfect, two perfect
	one perfect	40	16.4	none, two perfect
	two perfect	40	16.7	none, one perfect
	early	40	13.7	----
L	140	80	14.2	----
	230	80	17.2	----
T	600	80	14.0	----
	1000	80	17.4	----
S	permissive	32	10.9	----
	perm.-pro.	32	13.5	----
	pro.-perm.	32	14.7	----
	pro.-lag	32	19.4	pro.-lead
	pro.-lead	32	19.9	pro.-lag

Table 33. ANOVA results for stopped delay at the four-approach intersection.

Factor or interaction	Degrees of freedom	Sum of squares	F value	Significance probability
SP	1	1.77	0.8	0.3876
FA	1	277.9	118.0	0.0001
P	3	310.6	44.0	0.0001
L	1	223.0	94.7	0.0001
T	1	134.5	57.1	0.0001
S	4	1597.7	169.5	0.0001
SP*FA	1	13.3	5.6	0.0194
SP*P	3	123.0	17.4	0.0001
SP*L	1	0.0	0.0	0.9459
SP*T	1	0.0	0.0	0.9716
SP*S	4	13.0	1.4	0.2446
FA*P	3	124.1	17.6	0.0001
FA*L	1	0.1	0.0	0.8731
FA*T	1	2.8	1.2	0.2749
FA*S	4	25.9	2.8	0.0323
P*L	3	2.4	0.3	0.7908
P*T	3	19.9	2.8	0.0430
P*S	12	152.3	5.4	0.0001
L*T	1	2.7	1.1	0.2892
L*S	4	70.5	7.5	0.0001
T*S	4	51.4	5.4	0.0005
ERROR	102	240.3	----	------
TOTAL	159	3387.2	----	------

The notation "SP*FA," for example, means the interaction between the speed factor (SP) and the signal type factor (FA).

Table 34. Mean values of stopped delay for main effects at the four-approach intersection.

Factor	Level	Number of observations	Mean stopped delay, seconds per vehicle	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
SP	30	80	9.5	50
	50	80	9.3	30
FA	fixed	80	10.8	----
	actuated	80	8.1	----
P	none	40	10.2	one perfect, two perfect
	one perfect	40	10.4	none, two perfect
	two perfect	40	10.1	none, one perfect
	early	40	7.0	----
L	140	80	8.3	----
	230	80	10.6	----
T	600	80	8.5	----
	1000	80	10.4	----
S	permissive	32	5.2	----
	perm.-pro.	32	7.4	----
	pro.-perm.	32	8.5	----
	pro.-lag	32	12.8	pro.-lead
	pro.-lead	32	13.3	pro.-lag

interaction between signal type and left turn signal type (FA*S) was significant at the 0.05 level, mainly because there was no difference between protected-lagging and protected-leading for fixed-time signals and about a one second difference for actuated signals. Finally, the interaction between left turn volume level and left turn signal type (L*S) was also significant at the 0.05 level, because both kinds of protected signals fared relatively better when left turn volumes were lower.

The ANOVA results for stops per vehicle are given in Table 35, while the means for each level of each factor are given in Table 36. The results were very similar to those for delay with the only major difference being the significance of the L*S interaction. This interaction was significant at the 0.05 level primarily because both types of protected signal performed better relative to other signals when left turn volumes were lower.

Intersections with Three Approaches

Experiment Set-Up

Intersections with three approaches were of interest in this research because they are common and have great potential for safety benefits with lagging sequences. Factors and levels for the simulation experiment included:

- P: none, left direction perfect, opposite direction perfect, and both directions perfect;
- L: 140 and 230 vph;
- T: 400, 600, 800, and 1000 vph; and
- S: permissive, protected-permissive, and permissive-protected.

Table 35. ANOVA results for the number of stops per vehicle at the four-approach intersection.

Factor or interaction	Degrees of freedom	Sum of squares	F value	Significance probability
SP	1	0.0280	11.6	0.0010
FA	1	0.0987	40.9	0.0001
P	3	0.7303	100.9	0.0001
L	1	0.2225	92.2	0.0001
T	1	0.0308	12.8	0.0005
S	4	0.9221	95.5	0.0001
SP*FA	1	0.0000	0.0	0.9123
SP*P	3	0.3906	54.0	0.0001
SP*L	1	0.0000	0.0	0.9426
SP*T	1	0.0010	0.4	0.5309
SP*S	4	0.0052	0.5	0.7082
FA*P	3	0.0644	8.9	0.0001
FA*L	1	0.0022	0.9	0.3449
FA*T	1	0.0036	1.5	0.2261
FA*S	4	0.0173	1.8	0.1364
P*L	3	0.0059	0.8	0.4909
P*T	3	0.0226	3.1	0.0292
P*S	12	0.1728	6.0	0.0001
L*T	1	0.0452	18.7	0.0001
L*S	4	0.0387	4.0	0.0047
T*S	4	0.0422	4.4	0.0026
ERROR	102	0.2462	----	------
TOTAL	159	3.0901	----	------

The notation "SP*FA," for example, means the interaction between the speed factor (SP) and the signal type factor (FA).

Table 36. Mean values of stops per vehicle for main effects at the four-approach intersection.

Factor	Level	Number of observations	Mean stops per vehicle	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
SP	30	80	0.45	----
	50	80	0.48	----
FA	fixed	80	0.49	----
	actuated	80	0.44	----
P	none	40	0.56	----
	one perfect	40	0.49	----
	two perfect	40	0.44	----
	early	40	0.38	----
L	140	80	0.43	----
	230	80	0.50	----
T	600	80	0.45	----
	1000	80	0.48	----
S	permissive	32	0.35	----
	perm.-pro.	32	0.43	----
	pro.-perm.	32	0.46	----
	pro.-lag	32	0.54	pro.-lead
	pro.-lead	32	0.56	pro.-lag

Again, these variables applied only to the major street of interest. The term "left direction" in the progression levels given above indicated the major street approach from which left turns are made, while the term "opposite direction" indicated the major street approach from which left turns are prohibited.

The network of streets and intersections simulated in this experiment is shown schematically in Figure 10. Data were analyzed only for vehicles on the two major street approaches to node 62. In fact, Figure 10 shows that no minor street approach was used in this network. This was possible because the signal at node 62 was never actuated and there was no right turn on red allowed at node 62. Other features of the simulated network for this experiment included:

- a desired approach speed of 30 mph,

- no right turn lane,

- a left turn lane with a capacity of ten vehicles, and

- a pedestrian volume at node 62 of 100 to 250 crossing pedestrians per hour.

SOAP [FHWA, 1985] was again the package used to insure that near optimal left turn phase splits were employed. As in central Indianapolis, a 70-second cycle, a four-second yellow phase and no all-red phase were employed.

A factorial experiment with one replication (96 simulation runs) was con-

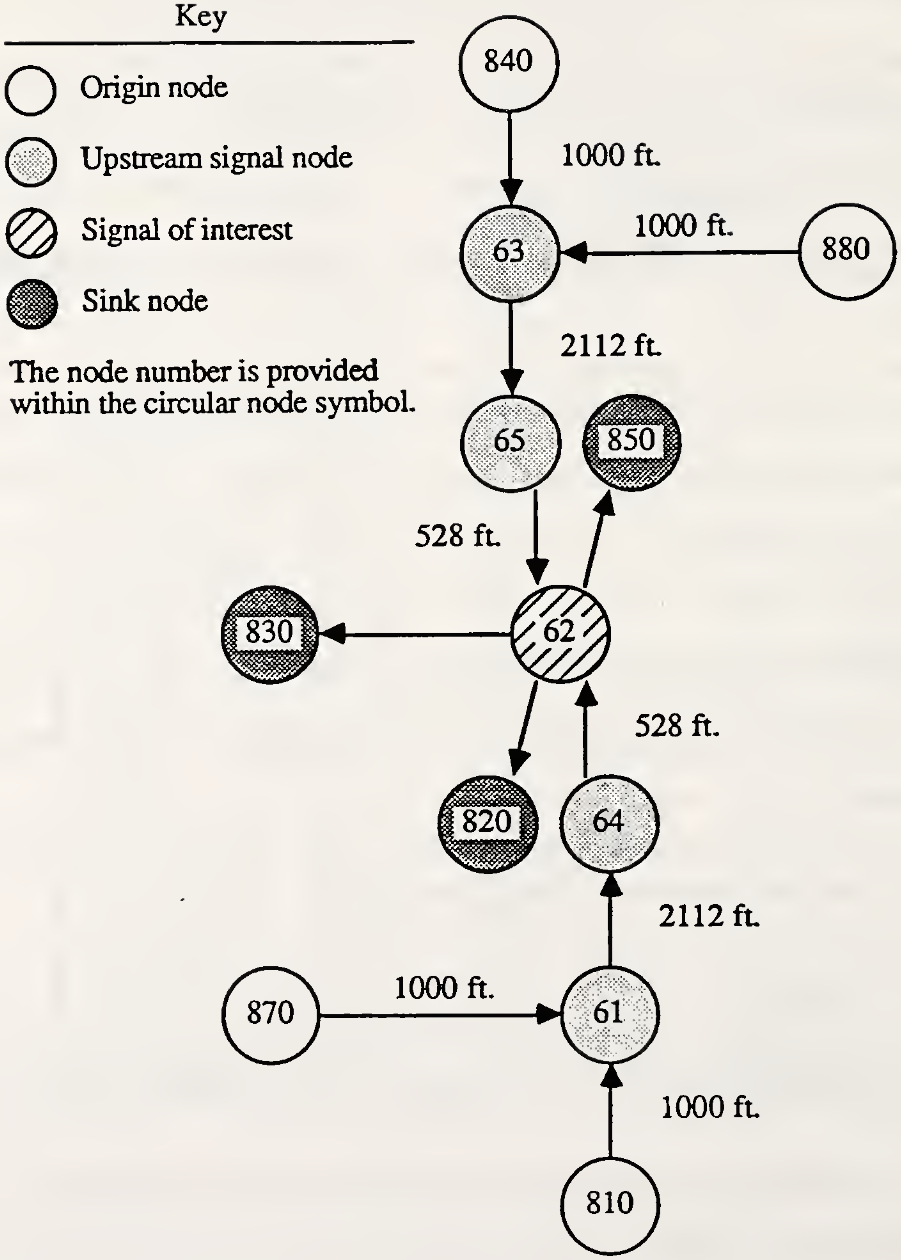


Figure 10. NETSIM nodes and links for intersection with three approaches.

ducted using the variables and levels listed above. Interactions of three or more factors were again assumed to be negligible. ANOVA was the main statistical tool used to investigate the variables and two-way interactions.

Results

Coded data for all 96 runs in this experiment are provided in Appendix A. The same three MOE's as previously described (delay, stopped delay, and number of stops) were computed from the raw data and analyzed using SAS.

Table 37 shows the ANOVA table for the delay MOE in this experiment. All four main effects (P, L, T, and S) were significant at the 0.05 level. Table 38 gives the means for each level of each main effect, and reveals that progression in both directions, lower left turn volumes and lower through volumes were associated with less delay. Among the levels of S, permissive caused the least delay while the mean values of delay for the permissive-protected and protected-permissive signals were virtually equal. A Student-Newman-Keuls test showed no significant difference between the means for the protected-permissive and permissive-protected signals. In addition, the L*S and T*S interactions were significantly related to delay. For both interactions, the permissive signal fared better in relation to the other signals when the lowest volumes were modelled. Tables 39 and 40 show the ANOVA table and the means for the main effects, respectively, for stopped delay and reveal the same trend as given above for delay.

Tables 41 and 42 give the ANOVA table and the means of the levels of the main effects for the stops per vehicle MOE. All four main effects and two of the interactions involving S were significantly related to stops per vehicle. Lower left turn volumes and progression in both directions were associated

Table 37. ANOVA results for delay at the three-approach intersection.

Factor or interaction	Degrees of freedom	Sum of squares	F value	Significance probability
L	1	3.3	14.2	0.0004
T	3	81.6	116.6	0.0001
P	3	272.2	389.5	0.0001
S	2	218.3	467.7	0.0001
L*T	3	0.3	0.4	0.7272
L*P	3	1.4	2.0	0.1244
L*S	2	1.8	3.8	0.0271
T*P	9	3.1	1.5	0.1799
T*S	6	6.9	5.0	0.0004
P*S	6	0.4	0.3	0.9418
ERROR	57	13.3	----	------
TOTAL	95	589.9	----	------

The notation "L*T," for example, means the interaction between the left turn volume factor (L) and the through volume factor (T).

Table 38. Mean values of delay for main effects at the three-approach intersection.

Factor	Level	Number of observations	Mean delay, seconds per vehicle	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
P	none	24	11.7	----
	left dir.	24	9.1	----
	opposite dir.	24	9.5	----
	both dirs.	24	7.0	----
L	140	48	9.2	----
	230	48	9.5	----
T	400	24	8.4	----
	600	24	8.7	----
	800	24	9.6	----
	1000	24	10.8	----
S	permissive	32	7.2	----
	perm.-pro.	32	10.4	pro.-perm.
	pro.-perm.	32	10.4	perm.-pro.

Table 39. ANOVA results for stopped delay at the three-approach intersection.

Factor or interaction	Degrees of freedom	Sum of squares	F value	Significance probability
L	1	1.4	7.8	0.0071
T	3	31.5	57.2	0.0001
P	3	331.7	602.8	0.0001
S	2	170.0	463.3	0.0001
L*T	3	0.1	0.2	0.8695
L*P	3	1.4	2.6	0.0591
L*S	2	1.3	3.5	0.0382
T*P	9	2.5	1.5	0.1651
T*S	6	4.7	4.3	0.0013
P*S	6	0.3	0.3	0.9356
ERROR	57	10.5	---	-----
TOTAL	95	555.4	---	-----

The notation "L*T," for example, means the interaction between the left turn volume factor (L) and the through volume factor (T).

Table 40. Mean values of stopped delay for main effects at the three-approach intersection.

Factor	Level	Number of observa-tions	Mean stopped delay, seconds per vehicle	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
P	none	24	8.5	----
	left dir.	24	5.7	----
	opposite dir.	24	6.0	----
	both dirs.	24	3.3	----
L	140	48	5.8	----
	230	48	6.0	----
T	400	24	5.4	600
	600	24	5.4	400
	800	24	6.0	----
	1000	24	6.8	----
S	permissive	32	4.0	----
	perm.-pro.	32	6.8	pro.-perm.
	pro.-perm.	32	6.8	perm.-pro.

Table 41. ANOVA results for the number of stops per vehicle at the three-approach intersection.

Factor or interaction	Degrees of freedom	Sum of squares	F value	Significance probability
L	1	0.0123	51.7	0.0001
T	3	0.0187	26.3	0.0001
P	3	1.4257	2002.8	0.0001
S	2	0.1478	311.4	0.0001
L*T	3	0.0005	0.6	0.5894
L*P	3	0.0028	3.9	0.0129
L*S	2	0.0021	4.4	0.0174
T*P	9	0.0089	4.2	0.0004
T*S	6	0.0043	3.0	0.0124
P*S	6	0.0006	0.4	0.8581
ERROR	57	0.0135	----	------
TOTAL	95	1.6236	----	------

The notation "L*T," for example, means the interaction between the left turn volume factor (L) and the through volume factor (T).

Table 42. Mean values of stops per vehicle for main effects at the three-approach intersection.

Factor	Level	Number of observa-tions	Mean stops per vehicle	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
P	none	24	0.16	----
	left dir.	24	0.33	opposite direction
	opposite dir.	24	0.32	left direction
	both dirs.	24	0.50	----
L	140	48	0.32	----
	230	48	0.34	----
T	400	24	0.32	600
	600	24	0.31	400
	800	24	0.33	----
	1000	24	0.35	----
S	permissive	32	0.27	----
	perm.-pro.	32	0.35	----
	pro.-perm.	32	0.36	----

with fewer stops. Lower through volumes also meant fewer stops. A Student-Newman-Keuls test revealed no significant difference between the 400 and 600 vph levels of through volume. The permissive signal was again the superior level of S, but for this MOE permissive-protected signals were significantly better than protected-permissive signals, causing about one percent fewer stops. The L*S interaction was significant due to relatively low values of stops per vehicle for permissive signals with a low left turn volume, while T*S interaction was significant because of relatively low values of stops per vehicle with permissive signals and a high through volume.

The suggestion from the literature review, that the time at which vehicles arrive at the left turn signal is a critical consideration when choosing between leading and lagging sequences, was tested during this experiment. For the 16 runs with a progression class of "perfect left direction" or "perfect both directions" and protected-permissive signals, the signal offsets were changed so that the front edge of the progression band along the major street arrived at the signal as the yellow arrow indication ended. The 16 new data items were substituted into the remainder of the data set and SAS was used to make new statistical computations. The only changes from the results given previously were to S and the P*S interaction. Figure 11 contains a plot of delay versus progression class for each level of S and shows clearly that changing the left direction and both direction progression classes meant a clear advantage for the lagging over the leading sequence. Similar plots for the other two MOE´s would have shown the same pattern. A Student-Newman-Keuls test revealed that for each of the three MOE´s the lagging sequence enjoyed a large and significant advantage over the leading sequence with the revised progression levels.

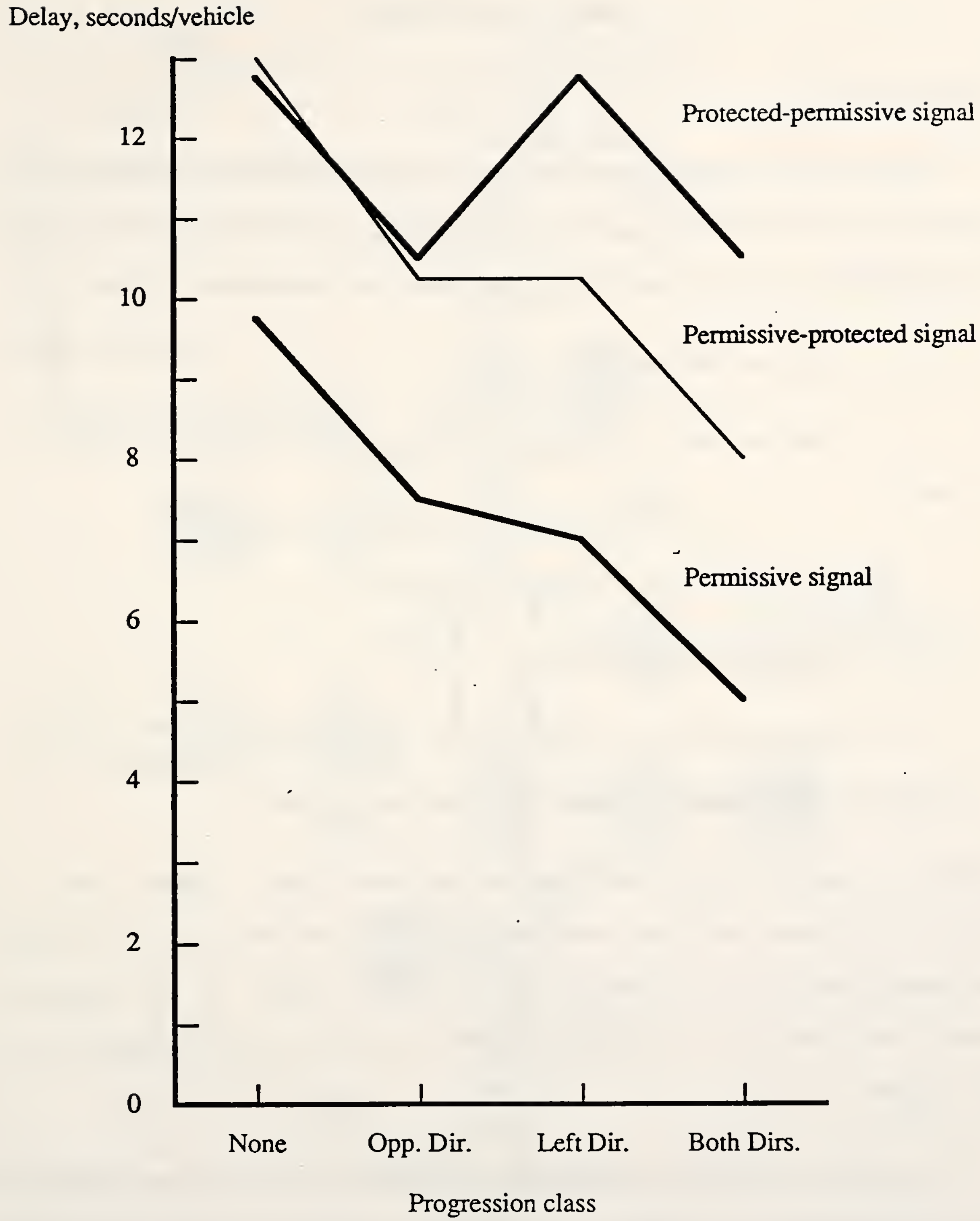


Figure 11. Delay for the three-approach experiment with a revised progression definition.

Diamond Interchanges

Experiment Set-Up

Diamond interchanges where both ramp terminals had signals with left turn phases were of interest for this research. Factors and levels for the simulation experiment to investigate those locations included:

- L: 200 and 400 vph;
- T: 600 and 1000 vph (opposing the left turn to the ramp);
- P: none and perfect in both directions;
- FA: fixed-time and actuated; and
- S: permissive, protected-permissive, permissive-protected, protected-leading, and protected-lagging.

Volumes were equal in both directions on the major street. Higher left turn volumes were used in this experiment than in the three- or four-approach experiments based on data collected during the peak hours at all signalized diamond interchanges in Indiana by INDOT where both ramp terminals had left turn signals.

The network of streets and intersections simulated in this experiment is shown schematically in Figure 12. The mean values of the three usual MOE´s (weighted by the number of approach vehicles) for the two approaches to node 61 and the two approaches to node 66 on the major street were analyzed.

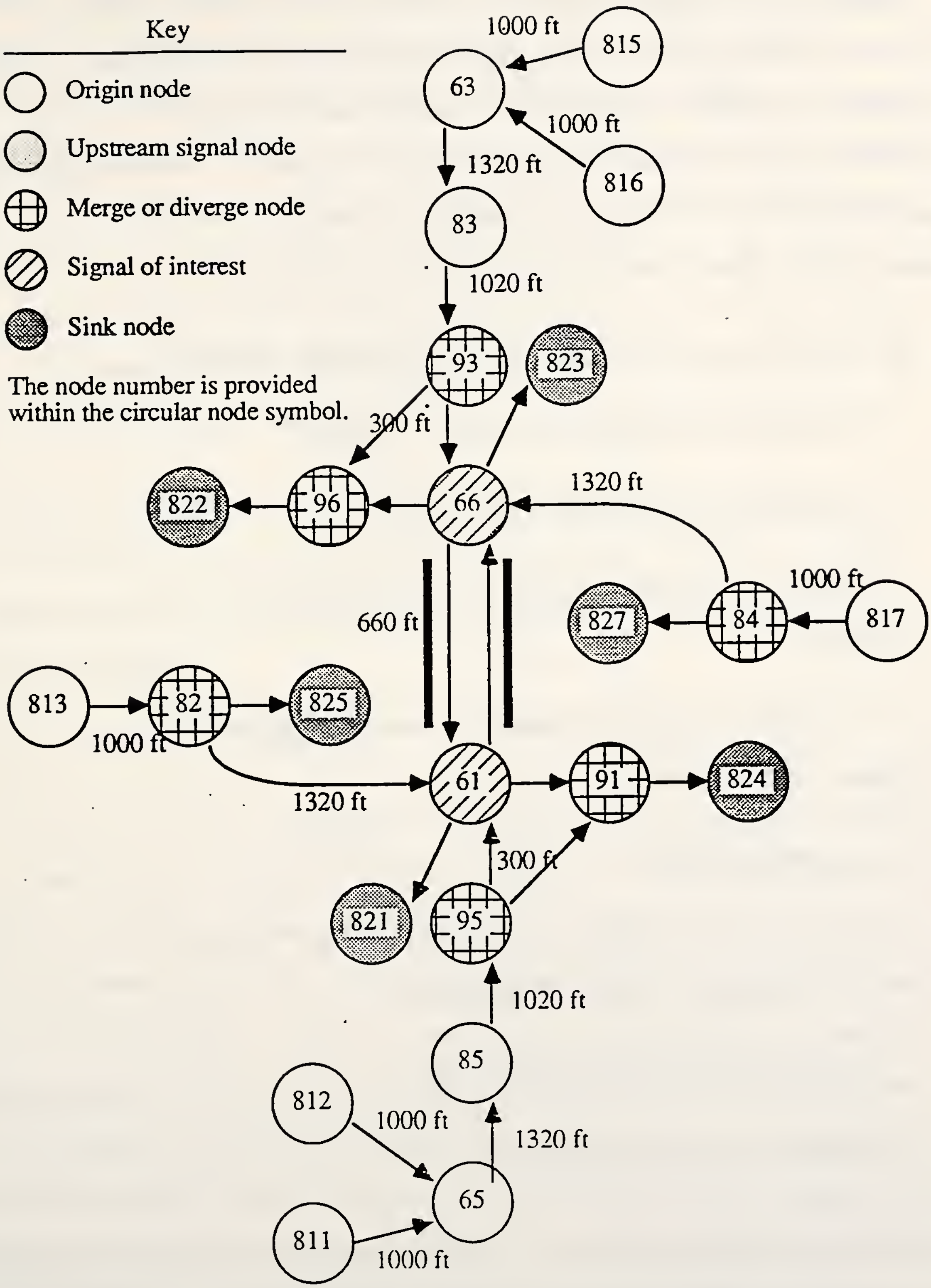


Figure 12. NETSIM nodes and links for the diamond interchange.

Figure 12 illustrates that the right turns to the ramps from the major street were channelized in the simulation, as they are generally at diamond interchanges in Indiana. Right-turning traffic departed the major street at nodes 95 and 93, and joined the ramps at nodes 91 and 96, respectively. Yield signs controlled the right-turning traffic at nodes 91 and 96. Thus, only through traffic opposed vehicles turning left to the ramps.

Other features of the model for this experiment included:

- two-lane major street and ramp approaches,
- desired approach speeds of 45 mph,
- major street left turn lanes with the capacity of 11 vehicles,
- no grades on any approaches (typical for Indiana diamond interchanges),
- no pedestrians,
- volumes of 400 vph for right turns to each ramp and for left and right turns from each ramp,
- four-second yellow intervals, and
- one-second all-red intervals.

SOAP [FHWA 1985] provided signal timing parameters for use in the experiment. PASSER III-88 [Fambro et al. 1988], a program designed to optimize the operation of fixed-time signals at diamond interchanges, was employed to pro-

vide offsets between the signals at nodes 61 and 66 for each combination of volume classes. These offsets were kept constant for a given combination of volume classes regardless of the value of the progression variable. The progression variable, then, affected only the offsets and timings of the signals at nodes 85, 65, 83, and 63 (i.e., nodes that were outside the diamond). Keeping the offsets constant within the diamond also meant that the signals at the two ramp terminals never acted in isolation, in keeping with standard practice. The actuated signal parameters used in this experiment were the same as in the four-approach intersection experiment for coordinated signals.

A factorial experiment with one replication (80 simulation runs) was conducted. Interactions of three or more factors were again assumed to be negligible. ANOVA was the primary statistical tool used to investigate the factors and two-way interactions.

Special Limitations of this Experiment

The diamond interchange experiment had several unique limitations which had to be considered when the results were analyzed. One major limitation was the inability of NETSIM to model a "four-phase" leading left turn signal operation. Four-phase control is a leading phasing scheme and is shown in Figure 13. A four-phase scheme could mean substantial delay savings over competing lagging schemes at certain intersections. Four-phase control is made possible by the signals at the two ramp terminals acting as one. For fixed-time signals, this is simply a matter of establishing the proper offset between the signals, and NETSIM could model these signals. However, an actuated four-phase system requires much closer coordination between the signals at the ramp terminals than NETSIM is capable of modelling. NETSIM would not be able to

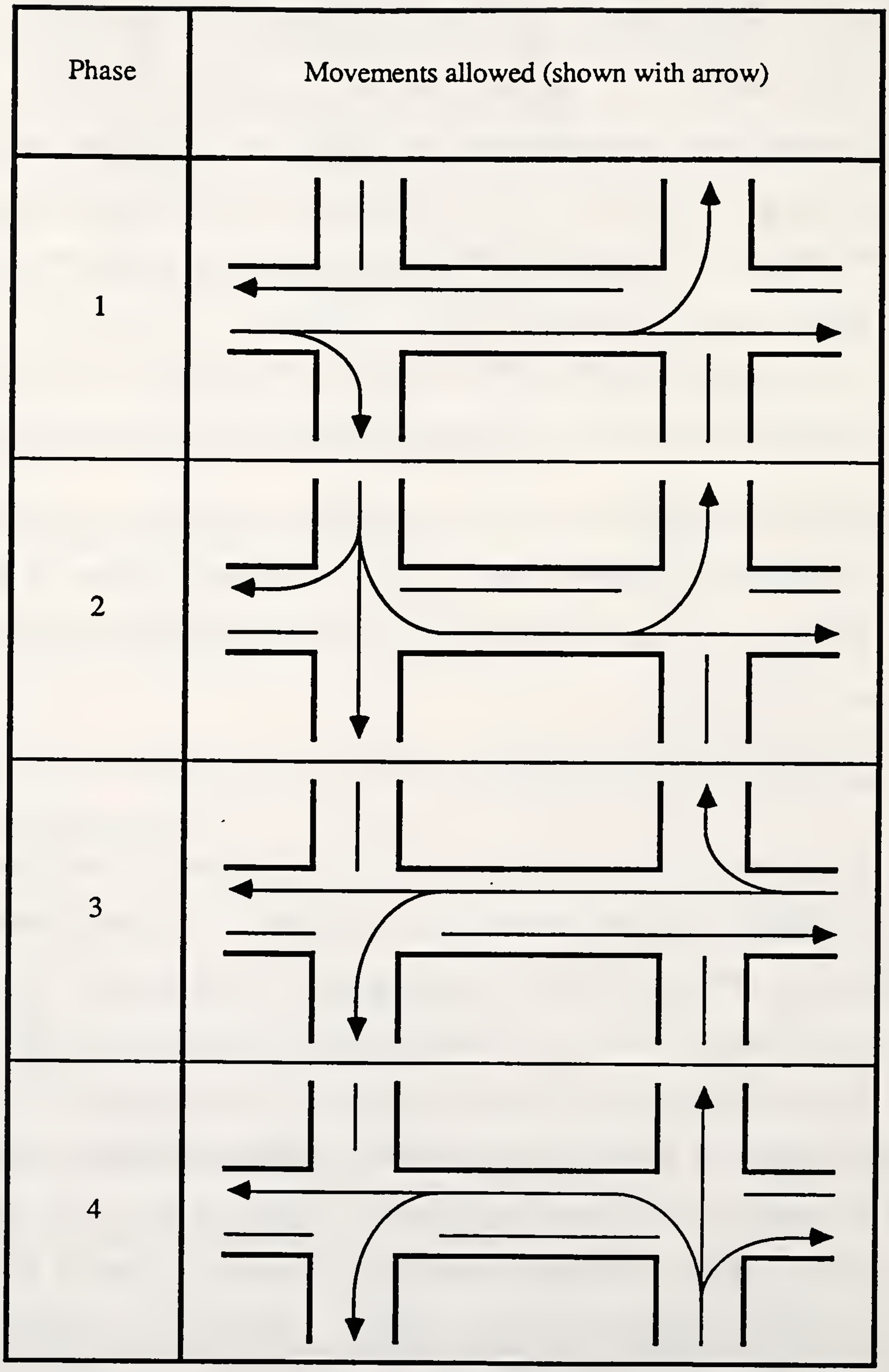


Figure 13. Four-phase signal control at a diamond interchange.

have the signal at node 66 (Figure 12) respond to a detector on link 82,61, for example, as actuated four-phase control requires. The offsets between ramp terminal signals for the leading fixed-time combinations in this experiment were not very different from the offsets for four-phase operation, so for fixed-time signals the bias against the leading sequence was not large. However, the bias against the leading sequence must be considered in arriving at conclusions based on this experiment.

Another major limitation during this experiment was the inability of NETSIM to model the fact that at diamond interchanges in Indiana (and elsewhere where no frontage roads are provided) few vehicles turning left off a ramp will immediately turn left onto the freeway at the other end of the diamond. Because NETSIM assigned approaching vehicles to turn at an intersection at random regardless of their prior paths, the model highly over-estimated the number of vehicles making such U-turns at the diamond interchange. The effects from this limitation on the leading and lagging issue are not known. However, the limitation probably resulted in a general under-estimation of delay by the model as compared to real traffic, because the traffic flows making a given maneuver would have been much more concentrated without those U-turns. The validation results presented for one-way pairs (which are essentially the same as diamond interchanges in terms of traffic on the crossing street) earlier in this chapter provide evidence to support the claim of under-estimation due to the U-turns. At the 18th and Salem intersection, where such U-turns were observed to be rare in the field, NETSIM consistently under-estimated delay in comparison to the field data. Meanwhile, at the Ohio and Delaware intersection where such U-turns were common due to the presence of many trip origins and destinations in the immediate vicinity, NETSIM estimates of delay were

more even with field estimates.

Results

Coded data for all 80 runs in this experiment are provided in Appendix A. Table 43 shows the ANOVA results for the delay MOE. The L, T, FA, and S factors were all significant in explaining the variation in delay at the 0.05 level. Table 44 provides the mean values for all levels of each main effect, and shows that lower left turn volumes, lower through volumes, and fixed-time signals led to lower amounts of delay. Among the signals, permissive again meant less delay, followed by permissive-protected, protected-permissive, protected-lagging, and protected-leading. A surprising result on Table 44 was that the means for the protected-permissive and protected-lagging signals were not significantly different. This result may be because at high volumes, traffic moves through intersections with protected-permissive and permissive-protected signals in much the same way that it moves through intersections with protected signals. The interaction T*S was significant, in fact, (Table 43) because at high through volumes the protected signals performed relatively better.

Tables 45 and 46 contain the ANOVA results and the means of the main effects for the stopped delay MOE. The stopped delay results were very much like the delay results, except that the progression variable was also significant, with no progression associated with less stopped delay. The results for S for stopped delay were slightly different from the delay results, in that the permissive signal mean was not significantly different from the mean for the permissive-protected signal. In fact, the permissive-protected signal actually had a lower mean value for stopped delay when

Table 43. ANOVA results for delay at the diamond interchange.

Factor or interaction	Degrees of freedom	Sum of squares	F value	Significance probability
L	1	1103.3	211.1	0.0001
T	1	245.9	47.1	0.0001
P	1	18.2	3.5	0.0680
FA	1	52.8	10.1	0.0026
S	4	1184.2	56.6	0.0001
L*T	1	65.8	12.6	0.0009
L*P	1	85.3	16.3	0.0002
L*FA	1	1.5	0.3	0.5940
L*S	4	14.8	0.7	0.5909
T*P	1	28.2	5.4	0.0244
T*FA	1	15.3	2.9	0.0931
T*S	4	69.0	3.3	0.0180
P*FA	1	15.8	3.0	0.0882
P*S	4	9.6	0.5	0.7663
FA*S	4	25.0	1.2	0.3244
ERROR	49	256.1	----	------
TOTAL	79	3191.0	----	------

The notation "L*T," for example, means the interaction between the left turn volume factor (L) and the through volume factor (T).

Table 44. Mean values of delay for main effects at the diamond interchange.

Factor	Level	Number of observa-tions	Mean delay, seconds per vehicle	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
L	200	40	13.1	----
	400	40	20.6	----
T	600	40	15.1	----
	1000	40	18.6	----
P	none	40	16.4	two perfect
	two perfect	40	17.3	none
FA	fixed-time	40	16.0	----
	actuated	40	17.7	----
S	permissive	16	11.9	----
	perm.-pro.	16	13.7	----
	pro.-perm.	16	17.3	protected-lagging
	pro.-lag	16	18.4	protected-permissive
	pro.-lead	16	23.0	----

Table 45. ANOVA results for stopped delay at the diamond interchange.

Factor or interaction	Degrees of freedom	Sum of squares	F value	Significance probability
L	1	800.9	180.5	0.0001
T	1	190.8	43.0	0.0001
P	1	42.7	9.6	0.0032
FA	1	61.0	13.8	0.0005
S	4	752.5	42.4	0.0001
L*T	1	68.5	15.4	0.0003
L*P	1	58.3	13.1	0.0007
L*FA	1	2.5	0.6	0.4562
L*S	4	10.4	0.6	0.6725
T*P	1	19.5	4.4	0.0413
T*FA	1	9.4	2.1	0.1522
T*S	4	61.4	3.5	0.0144
P*FA	1	13.0	2.9	0.0932
P*S	4	9.6	0.5	0.7057
FA*S	4	21.2	1.2	0.3262
ERROR	49	217.5	----	-----
TOTAL	79	2339.1	----	-----

The notation "L*T," for example, means the interaction between the left turn volume factor (L) and the through volume factor (T).

Table 46. Mean values of stopped delay for main effects at the diamond interchange.

Factor	Level	Number of observa-tions	Mean stopped delay, seconds per vehicle	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
L	200	40	7.3	----
	400	40	13.7	----
T	600	40	9.0	----
	1000	40	12.1	----
P	none	40	9.8	----
	two perfect	40	11.2	----
FA	fixed-time	40	9.6	----
	actuated	40	11.4	----
S	permissive	16	7.0	permissive-protected
	perm.-pro.	16	7.7	permissive
	pro.-perm.	16	10.5	protected-lagging
	pro.-lag	16	11.8	protected-permissive
	pro.-lead	16	15.5	----

through volumes were 1000 vph (9.3 to 10.1 seconds per vehicle). This result verifies the well-known point that there are high levels of volume (i.e., perhaps about 1000 vph for through traffic with at least 200 vph turning left at the diamond interchange being modelled in this experiment) above which permissive signals become less efficient than other left turn signal schemes. The volume levels used in this research, which were typical of volumes during the peak hours at many signalized intersections in Indiana, were not generally high enough to reach the point where any type of left turn protection was justified on the basis of mean delay for all approach vehicles.

Results for the diamond interchange experiment for stops per vehicle are given in Tables 47 and 48. Table 47 reveals that all main effects were significantly related to stops per vehicle, as were many two-way interactions including all four interactions involving S. Table 48 shows that lower left turn volumes, lower through volumes, and fixed-time signals led to fewer stops. "Perfect in both directions" caused fewer stops than other progression classes which contrasts with the results for the other MOE´s. The ranking of the signal schemes remained unchanged for this MOE as opposed to the other two MOE´s, but for this MOE each signal scheme was significantly different from the others. The interactions involving S were significant for a variety of interesting reasons. The L*S interaction was significant because higher left turn volumes meant a relatively good performance by the permissive signal. With higher through volumes, the permissive and the two protected signals fared much better relative to the other signals, which caused the T*S interaction to be significant. The P*S interaction was significant primarily because very few stops (less than 0.25 stops per vehicle) were required of vehicles approaching the permissive signals under the perfect progression case.

Table 47. ANOVA results for the number of stops per vehicle at the diamond interchange.

Factor or interaction	Degrees of freedom	Sum of squares	F value	Significance probability
L	1	0.4178	504.1	0.0001
T	1	0.0379	45.7	0.0001
P	1	0.0930	112.3	0.0001
FA	1	0.0197	23.7	0.0001
S	4	1.0308	310.9	0.0001
L*T	1	0.0001	0.1	0.7820
L*P	1	0.0113	13.6	0.0006
L*FA	1	0.0003	0.4	0.5056
L*S	4	0.0650	19.6	0.0001
T*P	1	0.0012	1.5	0.2332
T*FA	1	0.0013	1.6	0.2193
T*S	4	0.0156	4.7	0.0027
P*FA	1	0.0058	7.0	0.0111
P*S	4	0.0127	3.8	0.0087
FA*S	4	0.0329	9.9	0.0001
ERROR	49	0.0406	----	------
TOTAL	79	1.7860	----	------

The notation "L*T," for example, means the interaction between the left turn volume factor (L) and the through volume factor (T).

Table 48. Mean values of the number of stops per vehicle for main effects at the diamond interchange.

Factor	Level	Number of observa-tions	Mean stops per vehicle	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
L	200	40	0.39	----
	400	40	0.53	----
T	600	40	0.44	----
	1000	40	0.48	----
P	none	40	0.49	----
	two perfect	40	0.43	----
FA	fixed-time	40	0.44	----
	actuated	40	0.47	----
S	permissive	16	0.30	----
	perm.-pro.	16	0.38	----
	pro.-perm.	16	0.45	----
	pro.-lag	16	0.54	----
	pro.-lead	16	0.62	----

Finally, both lagging signals fared relatively better with fixed as opposed to actuated signal equipment, although the ranking of signals based on stops per vehicle remained unchanged from the ranking for the other MOE's even for actuated signals.

Utilization of Signal Phases Experiment

The proportions of left-turning vehicles which completed turns during various signal phases were investigated for leading and lagging sequences during this research using NETSIM. The proportions were of interest because of their relationship to delay. The protected-permissive and permissive-protected signals provide opportunities for left turns during the green and yellow ball intervals which are not provided by protected-only signals. Time is saved by vehicles turning on the green or yellow ball, as well as by vehicles on other approaches which may enjoy longer green phases due to a shorter green arrow phase. Therefore, if either leading or lagging sequences were found to allow more vehicles to turn on the green or yellow ball it would have a major delay advantage. The proportions were also of interest because of their relationship to safety. The literature reviewed in Chapter 2 was clear in supporting the case that protected-only signals, in which most vehicles turn left with a green arrow indication, are generally much safer than other signals in which more turns are completed during other phases. Thus, the phase sequence which caused more turns on the green arrow would enjoy a distinct safety advantage.

The proportion of left turns made during different signal phases has been investigated previously. Agent [1979a] studied the percent of turns made on the green ball for several protected-permissive signals in Kentucky as a sup-

plement to other studies of delay in an evaluation of such signals versus protected-leading signals. However, the review of the literature failed to uncover any previous data collected on the utilization of signal phases in relation to leading and lagging sequences. This experiment thus broke new ground by examining these proportions in relation to signal sequences.

Experiment Set-Up

The center of the network of nodes and links used in this experiment is shown in Figure 14. The network consisted of the same elements as the network for the four-approach intersection (see Figure 8) with the addition of nodes 73 and 75 through which left-turning traffic from the major street (from nodes 83 and 85) travelled and nodes 841, 842, 843, and 844 to which right-turning traffic from the major street and through traffic from the minor street travelled. Nodes 73 and 75 were placed one foot beyond the intersection, and at right-angles to the major street, while nodes 841-844 were placed at 45-degree angles to the major street (i.e., diagonals). Left-turning traffic was segregated from other traffic in order to obtain a count of the number of vehicles which had turned left during a particular time period. NETSIM intermediate statistics showed the number of vehicles which had discharged from each link up to the time the statistics were requested, so the total number of left turns in a given direction (say, towards node 73) was equivalent to the number of vehicles which had discharged from that link (61,73). The number of left turns toward node 73 completed, for instance, during a particular green ball phase was found by taking the difference between the number of vehicles discharged from link 61,73 before the green ball phase began from one set of intermediate statistics and the number of vehicles discharged from link 61,73 after the green ball phase ended from another set of intermediate statistics.

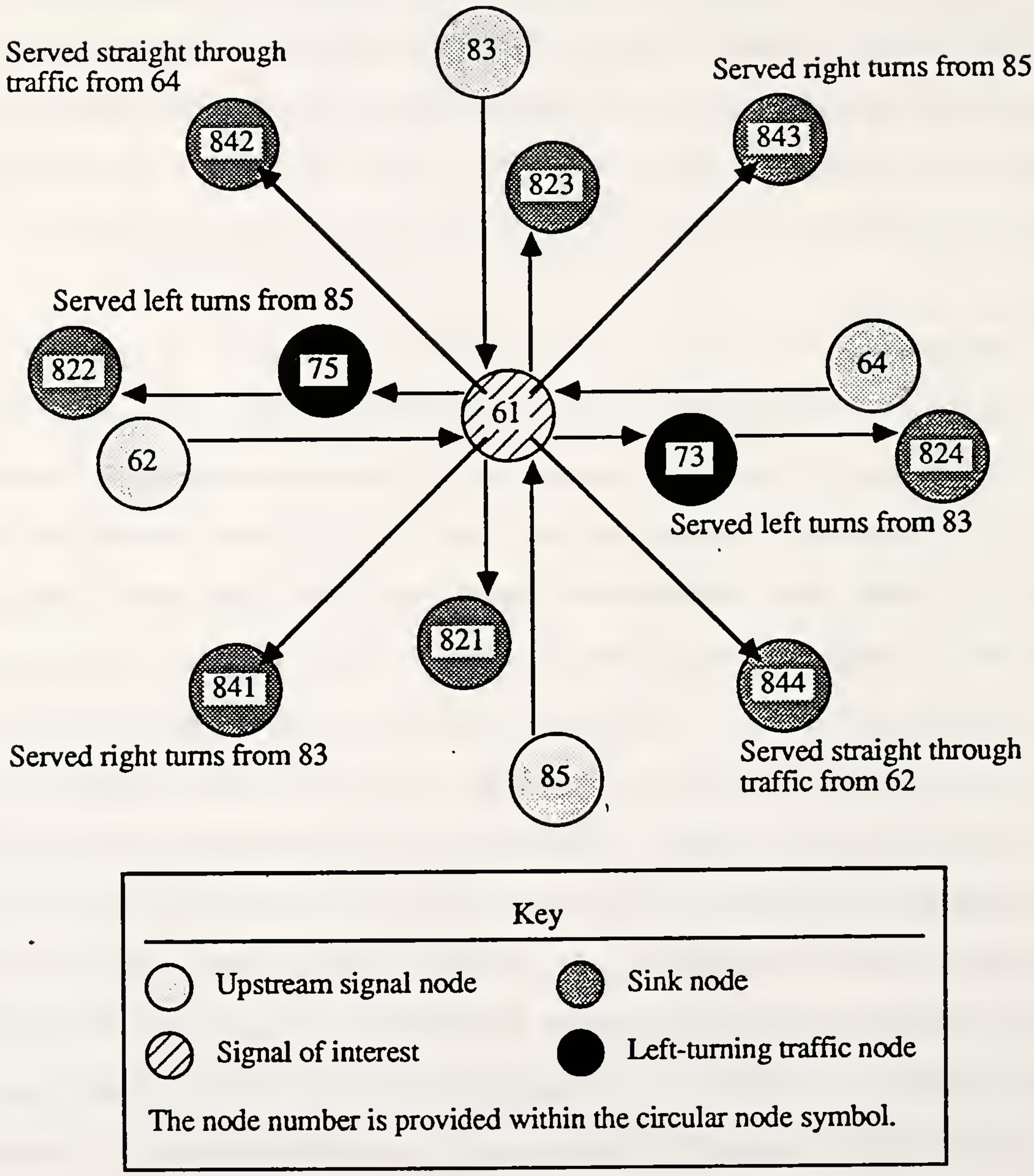


Figure 14. Center of NETSIM network for the utilization of signal phases experiment.

Making right turns from the major street into diagonal turns during this experiment had the effect of eliminating right turns on red since the right-turning vehicle had to cross, rather than join, traffic on the minor street. It may also have introduced some extra delay to the major street vehicles as compared to simulation runs during the four-approach experiment. The possibility of extra delay was investigated for a randomly selected combination of factors by comparing five runs with the previous four-approach network to five runs (with the same random number seeds) with the diagonal turns. Table 49 shows that when right turns on red were allowed on the previous four-approach network, significantly less delay was recorded than at the network with diagonal right turns. However, Table 49 also shows that the modifications to the network necessary to produce an estimate of vehicles turning on a given signal phase did not change the results from previous simulations when right turns on red were prohibited.

Data collection using the NETSIM intermediate output was cumbersome. NETSIM allows users to request intermediate output only at one particular time and at even increments of time thereafter (i.e., 68 seconds after the simulation period began and every 80 seconds thereafter) for a period of up to 999 seconds. Thus, to collect data on the number of left turns over the five different signal indications of a permissive-protected signal, five separate runs of NETSIM were necessary. Fortunately, two NETSIM runs with identical input files except for the intermediate output request produced identical values of MOE's. The restriction to 999 seconds meant that the simulation period consisted of 960 seconds (i.e., 12 signal cycles of 80 seconds each) rather than the usual 1800 seconds. An examination of the results for the proportion of vehicles turning on various signal cycles showed that the proportion was gen-

Table 49. Comparison of delay between normal four-approach network, four-approach network with no turn on red, and network revised for estimating left turns by phase.

Trial no.	NETSIM random number seed	Delay, seconds per vehicle			Difference in delay between networks	
		Normal network	Normal network with NTOR*	Diagonal right turn network	Diagonal and normal	Diagonal and NTOR*
1	42690342	14.1	16.1	16.5	2.4	0.4
2	10097325	14.3	16.8	16.8	2.5	0.0
3	37542048	15.8	16.0	15.5	-0.3	-0.5
4	08422689	15.1	16.3	16.5	1.4	0.2
5	99019025	14.8	16.1	17.3	2.5	1.2
Mean, all trials		14.8	16.3	16.5	1.7**	0.2***

* "NTOR" means no turn on red.

** Mean difference is significantly different from 0.0 at 0.05 level using t-test.

*** Mean difference is not significantly different from 0.0 at 0.05 level using t-test.

erally a very stable statistic through time, so the shorter simulation period did not have any practical effect. The data collection form developed for this experiment which allowed the recording on one sheet of data from all five NETSIM runs for a particular combination of factors is given in Figure 15.

Because the data collection process was cumbersome, the number of factors and levels examined was kept to a minimum. The list of factors and levels used included:

- SP: 30 and 50 mph;

- P: none, one direction perfect, both directions perfect, and early;

- L: 140 and 230 vph;

- T: 600 and 1000 vph; and

- S: protected-permissive and permissive-protected.

Only fixed-time signals were studied during this experiment. Besides data collection difficulties, there were reasons that other types of signals were not included in the experiment. The numbers of turns on the yellow and red indications at permissive signals have been researched extensively in the past, especially in regards to highway capacity analysis [Lin 1982]. Protected signals were not as interesting for this experiment because only three signal indications are presented to left-turning traffic and because it is highly unlikely that the proportion of left turns on a particular phase would differ between leading and lagging sequences (with all else constant). Actuated isolated signals were not of interest since almost all such installations on the

Run:	Cumulative number of vehicles which have completed left turns									
	Link 61,75					Link 61,73				
Lag:	mid red	end gb	end yb	end ga	end ya	mid red	end gb	end yb	end ga	end ya
Lead:	mid red	end ga	end ya	end gb	end yb	mid red	end ga	end ya	end gb	end yb
cycle 1										
cycle 2										
cycle 3										
cycle 4										
cycle 5										
cycle 6										
cycle 7										
cycle 8										
cycle 9										
cycle 10										
cycle 11										
cycle 12										
cycle 13										

Totals	Link 61,75	Link 61,73	Both links
gb			
yb			
ga			
ya			
red			
All ints.			

Other results	Link 85,61	Link 83,61
Pct stop delay		
Veh. trips		
Stops/veh.		
D-time/veh.		

Figure 15. NETSIM data collection form for the utilization of signal phases experiment.

Indiana state highway system were at high-speed intersections with only protected left turns. Finally, actuated coordinated signals were not included because they frequently function in a manner very similar to fixed-time signals, especially at the higher volume classes.

Signal timing and other parameters for this experiment were identical to those employed for the four-approach intersection experiment. Right turns on red were prohibited as discussed earlier.

A one-half replicate factorial experiment was designed. The equation used to generate the list of combinations was [Anderson and McLean 1974]:

$$A = X1 + X3 + X4 + X5 + X6 + X7, \text{ modulus } 2 \qquad (2)$$

where:

X7 = 0 for permissive-protected and 1 for protected-permissive signals, and

A, X1, X3, X4, X5, and X6 are as defined previously for equation 1.

No single factor or two-factor interaction was confounded with another single factor or two-factor interaction. Equation 2 produced a list of 32 combinations to be run, but the error term during an ANOVA with 32 runs (assuming again that interactions involving three or more factors were negligible) would have had only six degrees of freedom. Therefore, four of the 32 combinations were run again, with a different random number seed the second time, to boost the number of degrees of freedom in the error term to ten.

Results

A set of coded data for this experiment is provided in Appendix A. Since

delay, stopped delay, and the number of stops per vehicle were available from the output of NETSIM runs for this experiment, they were also recorded and analyzed. Table 50 contains a summary of the ANOVA results for those three MOE's regarding S, and shows that the trends which emerged from this experiment were identical to the trends for the three-approach intersection experiment. Basically, there was no difference between the signals in terms of delay and stopped delay, there was a small but statistically significant (in the ANOVA) difference in favor of the lagging sequence in the number of stops per vehicle, and no interactions involving S were statistically significant. Independent verification of the results with those from the three-approach experiment gives these results increased credibility. Appendix B contains, for the three MOE's, complete ANOVA results and mean values for each level of each main effect.

Eleven measures of the utilization of the various parts of the signal cycle were analyzed from the data collected for this experiment. The percent of left turns completed during the green ball, yellow ball, green arrow, yellow arrow, and red indications were analyzed. In addition, the percent of left turns completed during the ball (green or yellow), arrow (green or yellow), green (arrow or ball), and yellow (arrow or ball) indications were computed and analyzed. The percent of turns completed during the last yellow indication before the red indication (i.e., arrow for lagging and ball for leading) and the percent of turns completed during the last yellow indication plus the percent completed during the red indication were also analyzed.

The complete ANOVA results and the means of each level of each main effect are provided for all eleven measures in Appendix B. A summary of the

Table 50. Summary of ANOVA results for delay-related MOE's during the utilization of signal phases experiment.

MOE	Mean value of MOE for given level of S		Significance probability from ANOVA for S
	Permissive-protected	Protected-permissive	
Delay, seconds per vehicle	17.0	16.9	0.4176
Stopped, delay, sec. per veh.	10.3	10.4	0.1325
Stops per vehicle	0.477	0.493	0.0051

results for the signal sequence variable is provided in Table 51. The lagging signal had significantly (at the 0.05 level) more left turns on:

- the green ball indication,
- the yellow ball indication,
- green indications, and
- ball indications.

The leading signal had significantly more left turns on:

- the yellow arrow indication,
- the red indication,
- the last yellow indication before the red, and
- the last yellow indication before the red plus the red indication.

The magnitude of the differences noted above ranged from three percent to 31 percent in the case of the difference for the last yellow plus the red indications. There was no statistical difference between the signal levels for the percent of left turns on the green arrow indication, yellow indications, or arrow indications.

Only a few two-factor interactions involving S proved significant for the 11 measures studied. Lagging was relatively better for the percent of turns on the green ball indication with higher through volumes, and for the percent of turns on the green arrow indication with lower through volumes. Lagging

Table 51. Summary of ANOVA results on utilization of signal phases by left turn vehicles.

Interval(s)	Mean value of percent of left turns on the interval(s) for given level of S		Significance probability from ANOVA for S
	Permissive-protected	Protected-permissive	
Green ball	33	23	0.0001
Yellow ball	31	28	0.0150
Green arrow	25	20	0.0755
Yellow arrow	8	15	0.0008
Red	3	14	0.0001
Green (ball plus arrow)	58	44	0.0001
Yellow (ball plus arrow)	39	43	0.0945
Ball (green plus yellow)	64	51	0.0001
Arrow (green plus yellow)	32	35	0.1424
Last yellow before red	8	28	0.0001
Last yellow before red plus red	11	42	0.0001

was also relatively better for the percent of turns on the last yellow indication before the red with lower left-turning volumes. Leading fared relatively well, but was still not better than lagging, for the percent of turns on arrow indications and for the percent of turns on the last yellow indications before the red when no progression was modelled.

The trend which emerged from Table 51 was that, for the conditions tested, lagging meant more turns on the green and yellow ball indications while leading meant more turns near the end of the signal cycle. This trend helped explain the advantages lagging signals enjoyed in delay-related MOE's during various simulation experiments. The implications of this trend for safety are less obvious, however. The only well-established relationship between the utilization of various left turn phases and safety documented in the literature review held that safety increased as the percent of left turns which were made on arrow indications increased. Since there was no difference in the percent of left turns made on the green arrow indication or on arrow indications between leading and lagging, however, neither can be said to he safer based on this relationship.

Regarding the safety implications of the trend in the results noted above, there are two possible reasons that left turns which are made during the green or yellow ball indications at a lagging signal may be safer than turns at the end of a leading signal cycle. First, the leading turns at the end of the cycle could conflict with oncoming traffic and with cross-street traffic jumping into the intersection early, whereas the lagging turns on a ball indication in mid-cycle could conflict with cross-street drivers only when those drivers were making highly illegal maneuvers. Second, drivers contemplating left turns at the end of the leading cycle could feel more pressure

to turn (or subject themselves and other drivers in the queue to lengthy delays) than drivers contemplating turns on a ball indication in the lagging cycle. More pressure to turn could result in an acceptance of greater risks. There are no data to substantiate the above two reasons; therefore, a cautious outlook was assumed in incorporating this trend into the guidelines on leading and lagging sequences.

Actual Intersections

To lend further credibility to the simulation results given in this chapter, one final simulation experiment was conducted. Data from three actual intersections in Indianapolis were input in the simulation model instead of the representative values which were input for other experiments. These actual intersection data were used to compare the existing protected-permissive signals to permissive-protected signals.

Experiment Set-Up

Table 52 shows the actual intersection data input into NETSIM. The intersections were chosen for study because of the variety of conditions they possessed, because they were in the same city, and because data were available for them. One intersection was downtown and had a fixed-time coordinated signal, one intersection was in an older urban area about a mile from the center of downtown and had a fixed-time coordinated signal, and the third intersection was an isolated ramp terminal (the other half of the diamond interchange was controlled by a stop sign) with an actuated signal about ten miles from downtown. All three intersections had three approaches.

Conditions during five different time periods were modelled for each

Table 52. Characteristics of intersections where actual input data were collected.

Characteristic	Ohio at Delaware	South at Delaware	86th at SB I-465 Ramp
Area	Downtown	Urban	Suburban
Number of approaches	3	3	3
Number of through lanes in each direction on major street	2-3*	2	2
Left turn lane	No	Yes	Yes
Right turn lane and/or channel	Neither	Neither	Both
Right turn on red	No	Yes	Yield control
Speed limit, mph, left turn approach	25	30	45
Speed limit, mph, opposite approach	25	30	55
Signal equipment	Fixed-time	Fixed-time	Actuated
Signal coordination	Yes	Yes	No
Distance to upstream signal, ft, left turn approach	528	528	2640**
Distance to upstream signal, ft, opposite approach	528	2640**	5280**
Overnight left turn volume, vph	25	24	97
Morning peak left turn volume, vph	153	72	514
Midday left turn volume, vph	121	94	412
Evening peak left turn volume, vph	142	149	773
Other hours left turn volume, vph	76	63	296
Overnight opposing through vol., vph	53	72	34
Morning peak opp. through vol., vph	619	342	405
Midday opposing through vol., vph	252	345	144
Evening peak opp. through vol., vph	328	531	137
Other hours opp. through vol., vph	169	216	103

* Three during morning and evening peak hours, two at all other times.

** Assumed.

intersection, including overnight (0000 to 0600), morning peak (0700 to 0900), midday (0900 to 1500 and 1800 to 2000), evening peak (1500 to 1800), and other (0600 to 0700 and 2000 to 0000). Average traffic volumes for each movement were calculated for each time period from INDOT counts, conflict study (Chapter 4) counts, or standard INDOT factors. Thirty-minute simulations were run. Existing signal timing parameters were obtained from INDOT and from the City of Indianapolis. Geometric data were collected during visits to the sites. Data on signals upstream of the intersection of interest were also obtained for the coordinated signals. The only changes made when modelling permissive-protected as opposed to the existing protected-permissive signal was in the sequence itself--no changes to the offsets to adjacent signals, the time allotted to the left turn phase, or any other signal parameter were made.

ANOVA was the main statistical tool used to investigate the relationship between delay and stops per vehicle and the signal sequence. The experiment had three variables: intersection (I) at three levels, hour (H) at five levels, and signal sequence (S) at two levels. The factorial experiment was replicated twice, for a total of sixty NETSIM runs, using a different random number seed for each replicate.

Results

The coded data for this experiment are provided in Appendix A. The results from the simulation experiment using actual intersection data generally confirm the results from other simulations. The lagging sequence caused less delay and fewer stops than the leading sequence, especially when a fixed-time signal at a one-way pair was modelled and when left turn volumes were not at the peak levels.

The ANOVA results for delay are presented in Table 53. All factors and interactions were highly significant, including S and all interactions involving S. Table 54 provides the mean values for the levels of S. Lagging was the superior sequence overall, at each intersection, and for each time period. However, there was not much difference between the leading and lagging sequences at the 86th Street (actuated ramp) intersection or during the morning peak hours when the heaviest left turn and opposing volumes were generally present.

The results for the stops per vehicle MOE were very similar to the results for delay. Every main effect and interaction was again highly significant. The lagging sequence caused about 0.44 stops per vehicle, while the existing leading sequence caused about 0.58 stops per vehicle. The leading sequence again fared better, but was still not superior to the lagging sequence, at the 86th Street intersection and during the morning peak hours.

Chapter Summary

To investigate the relationship of delay and left turn signal sequences, the NETSIM simulation model was employed for a series of five separate factorial experiments. Comparisons of field data to NETSIM output, along with the long record of NETSIM in similar research and other recent validation efforts, demonstrated that the model produced reasonable results. Model inputs were based on a sample of Indiana intersections and were made with the goal of constructing a fair and representative test of the left turn signal alternatives. One of the five experiments generated data on the utilization of various signal phases by left-turning traffic which may have safety as well as delay implications.

Table 53. ANOVA results for delay for the experiment with actual intersection data.

Factor or interaction	Degrees of freedom	Sum of squares	F value	Significance probability
I	2	2068.2	1877.4	0.0001
H	4	142.0	64.4	0.0001
S	1	253.4	460.0	0.0001
I*H	8	20.5	4.6	0.0009
I*S	2	108.0	98.0	0.0001
H*S	4	38.5	17.5	0.0001
I*H*S	8	64.7	14.7	0.0001
ERROR	30	16.5	----	------
TOTAL	59	2711.9	----	------

The notation "I*H," for example, means the interaction between the intersection factor (I) and the hour factor (H).

Table 54. Mean values of delay for main effects for the experiment with actual intersection data.

Factor	Level	Number of observations	Mean delay, seconds per vehicle	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
I	Ohio @ Del.	20	17.0	----
	South @ Del.	20	20.0	----
	86th @ SB I-465	20	6.3	----
H	Overnight	12	12.2	----
	Morning peak	12	16.8	----
	Midday	12	14.2	Other
	Evening peak	12	15.2	----
	Other	12	13.6	Midday
S	Perm.-pro.	30	12.4	----
	Pro.-perm.	30	16.5	----

Data summarizing the relationships between the delay-related MOE´s and the various left turn signal types tested for each experiment are given in Table 55. The largest experiment involved intersections with four approaches, and showed that protected-permissive signals caused slightly more delay, stopped delay, and stops than permissive-protected signals. No actual differences between protected-lagging and protected-leading signals was detected. The experiment on intersections with three approaches was highlighted by the fact that there was little difference between the protected-permissive and permissive-protected signals in delay or stopped delay, but the latter caused fewer stops per vehicle. A variation on this experiment demonstrated the sensitivity of the lead and lag decision to the time in the signal cycle the progression band arrived at the left turn signal. The experiment on diamond interchanges documented the superiority of lagging over leading schemes in terms of delay and stops. The experiment on utilization of the signal phases provided evidence that under certain conditions a permissive-protected signal encouraged more left turns on the green ball indication, the yellow ball indication, and green indications. Meanwhile, more turns were made on the yellow arrow indication, on the red indication, and at the end of the signal cycle with the leading signal. The experiment with actual intersection data confirmed the superior efficiency of lagging over leading sequences for a limited range of intersection types. Several of the experiments also showed the relative superiority of permissive signals and the relative inferiority of protected-only signals in terms of delay.

The magnitudes of all the differences summarized above were documented and may be useful to engineers making traffic signal decisions. The results from this chapter should be used with the context in which they were produced

Table 55. Summary of relationship between MOE's and left turn signal types in the five simulation experiments.

Experiment	Left turn signal	Mean delay, sec/veh	Mean stopped delay, sec/veh	Mean stops per vehicle
Four approaches	Permissive	10.9	5.2	.35
	Permissive-protected	13.5	7.4	.43
	Protected-permissive	14.7	8.5	.46
	Protected-lagging	19.4	12.8	.54
	Protected-leading	19.9	13.3	.56
Three approaches	Permissive	7.2	4.0	.27
	Permissive-protected	10.4	6.8	.35
	Protected-permissive	10.4	6.8	.36
Diamond interchange	Permissive	11.9	7.0	.30
	Permissive-protected	13.7	7.7	.38
	Protected-permissive	17.3	10.5	.45
	Protected-lagging	18.4	11.8	.54
	Protected-leading	23.0	15.5	.62
Utilization of signal phases	Permissive-protected	17.0	10.3	.48
	Protected-permissive	16.9	10.4	.49
Actual intersections	Permissive-protected	12.4	no data	.44
	Protected-permissive	16.5	no data	.58

in mind. The limitations of the NETSIM model should be factored into any decision based on these results. Other important limitations of the experiments were the biases against protected-permissive signals in the four-approach intersection experiment (no phase overlap at actuated signals) and in the diamond interchange experiment (no "four-phase" operation).

CHAPTER 7 - CONCLUSIONS AND GUIDELINES

Lead Versus Lag Results

The primary purpose of this research was to produce guidelines for the use of leading and lagging signal phase sequences. The work elements undertaken to accomplish that purpose included a literature review, a motorist survey, a traffic conflict study, an analysis of accident data, and experiments with delay data from a traffic simulation model. The results from this work greatly expanded the knowledge base on the important lead and lag issue, but there are still several aspects of the issue which deserve future attention.

The major findings of the research are summarized in the following sections. First, the literature revealed, among other things, that:

1. A policy that allows the choice of either lead or lag at individual intersection approaches in a coordinated system with the aim of maximizing the through band width decreases delay.

2. Permissive-protected signals on one approach of an intersection must be accompanied by a protected phase of some sort for left turns on the opposite side (and if permissive-protected is provided on the opposite side the protected phases must begin simultaneously) or the potentially dangerous trapping phenomenon may occur.

3. Conflicting evidence has been published, but most of the literature backs the claim that lagging phase sequences are generally safer than leading phase se-

quences.

The motorist survey indicated that:

1. The leading phase sequence was preferred by far more respondents than the lagging phase sequence, but many other respondents expressed no preference so the strength of conviction in this preference was suspect.

2. Respondents gave three reasons about equally often for preferring the leading phase sequence: more like normal (i.e., more common), safer, and associated with less delay.

The traffic conflict study produced several noteworthy results on the relative safety of leading and lagging phase sequences, including:

1. The lagging phase sequence was associated with fewer left turn vehicle and pedestrian conflicts at the downtown comparison sites.

2. The lagging phase sequence was associated with fewer left turn and oncoming vehicle conflicts at the downtown and urban comparison sites.

3. Fewer left turn vehicles entered the suburban intersection with the lagging phase sequence on the red signal than the suburban intersection with the leading phase sequence.

4. The leading phase sequence was associated with

fewer indecision conflicts at all three pairs of intersections and especially at the suburban site.

The analysis of left turn accident data showed with limited sets of intersections with three approaches that:

1. No difference between the leading and lagging sets of intersections was observed for left turn accidents per left turn vehicle, but the lagging set had significantly fewer left turn accidents per total entering vehicle.

2. The lagging phase sequence intersections had a significantly smaller proportion of injury to total left turn accidents than the leading phase sequence intersections.

The simulation experiment on the utilization of the various signal phases contributed several safety-related results, including:

1. The lagging phase sequence had fewer stops per vehicle and had more vehicles turning on the green ball indication, the yellow ball indication, and green indications than the leading phase sequence.

2. The leading phase sequence had more vehicles turning on the yellow arrow indication, on the red indication, and at the end of the signal cycle than the lagging phase sequence.

Finally, the simulation experiments showed that:

1. There was no difference in delay between leading and lagging phase sequences at intersections with three approaches but lagging phase sequences caused fewer stops.

2. The status of the progression band, if any, relative to the signals on the approach with the left turn phase at an intersection made a vast difference in whether the leading or lagging phase sequence caused less delay.

3. Protected-lagging and protected-leading signals caused virtually equal amounts of delay and forced virtually equal numbers of stops at intersections with four approaches.

4. Protected-permissive signals caused slightly more delay than permissive-protected signals at intersections with four approaches. However, the ability of protected-permissive signals to overlap phases may close that gap at intersections with actuated signals.

5. At diamond interchanges, the lagging phase sequence was superior to the leading phase sequence in terms of both delay and stops.

Many of the results summarized above are mutally supportive. For instance, one of the reasons that the lagging phase sequence was found to be

safer was the greater separation of pedestrians from left turning traffic the lagging phase sequence allowed. This possibility was confirmed by data from the conflict study. In another example of mutual support, many survey respondents preferred leading phase sequences because they were more common. This helped support the finding that indecision conflicts were higher at the intersection in the suburban pair with the permissive-protected signal, which was the only permissive-protected signal in the area. The result that the permissive-protected signal was associated with fewer running the red signal conflicts at the suburban sites was supported by simulation results. The overall trend that lagging phase sequences were generally safer was supported by results from the traffic conflict study, the accident analysis, and the utilization of signal phases portion of the simulation work. Such mutually supporting results allowed confidence in the data and analysis methods employed to build throughout the present research.

The results from this research should be generalized very cautiously outside the bounds and the context of the data and analysis methods. Some of the more important limitations of the various data and collection methods were the exclusive focus on Indiana, the homogenous and small pools of intersections which provided conflict and accident data, and the relatively narrow ranges of factors included in the simulations experiments.

Guidelines

Based on the results summarized above and documented in the preceding chapters, the following guidelines were developed on the use of leading and lagging phase sequences in Indiana when some form of left turn phasing is warranted:

1. In coordinated signal systems, use should be made of any phasing sequence on a particular approach that will maximize the through band width.

2. Lagging instead of leading phase sequences should be used at isolated signals serving heavy pedestrian traffic.

3. Lagging instead of leading phase sequences should be used at isolated diamond interchanges or one-way pairs.

4. Permissive-protected signals should be used instead of protected-permissive signals where there is a history of or a potential for left turn and oncoming vehicle accidents but protected-leading or protected-lagging signals are not feasible alternatives.

5. Permissive-protected signals should be used instead of protected-permissive signals at isolated intersections with four approaches if the signals are fixed-time or incapable of overlapping phases.

6. Permissive-protected signals should not be used at an approach unless left turns from the opposite approach are prohibited, protected with protected-lagging or protected-leading signals, or made with a permissive-protected signal with the protected intervals starting for the opposing sides simultaneously.

7. At intersections where the above guidelines do not

fully answer the question of lead or lag, the existing phase sequence should not be changed or, if the signal or left turn protected phase is new, the phase sequence which is most common at similar sites in the area should be used.

Figure 16 contains a flow chart based on the guidelines to aid in making phase sequence decisions at individual intersections.

The guidelines have been developed with caution and changes in phase sequence are called for only in situations where a phase sequence has been proven clearly superior. This cautious approach is appropriate because of the litigious climate surrounding traffic control decisions and the likelihood that accidents may increase immediately after a change in traffic control such as from lead to lag. If future testing shows that the immediate negative impacts of changes in signal sequence are small, a more active role in changing intersections with the leading phase sequence to the lagging phase sequence should be assumed.

Other Results

Several of the results of this research did not apply to the lead and lag issue but may be useful in resolving other questions about left turn signals. The most pronounced result from the motorist survey was that protected schemes were much better understood than and preferred to other schemes tested. This result will bolster the confidence of beleaguered traffic engineers who install such schemes and then hear feedback only from people enraged by the additional delay. The motorist survey also produced the interesting result that the supplemental left turn sign "LEFT TURN YIELD ON GREEN Ø" actually

Answer the question in each rectangle for the intersection being analyzed until a recommendation (circled) is reached.

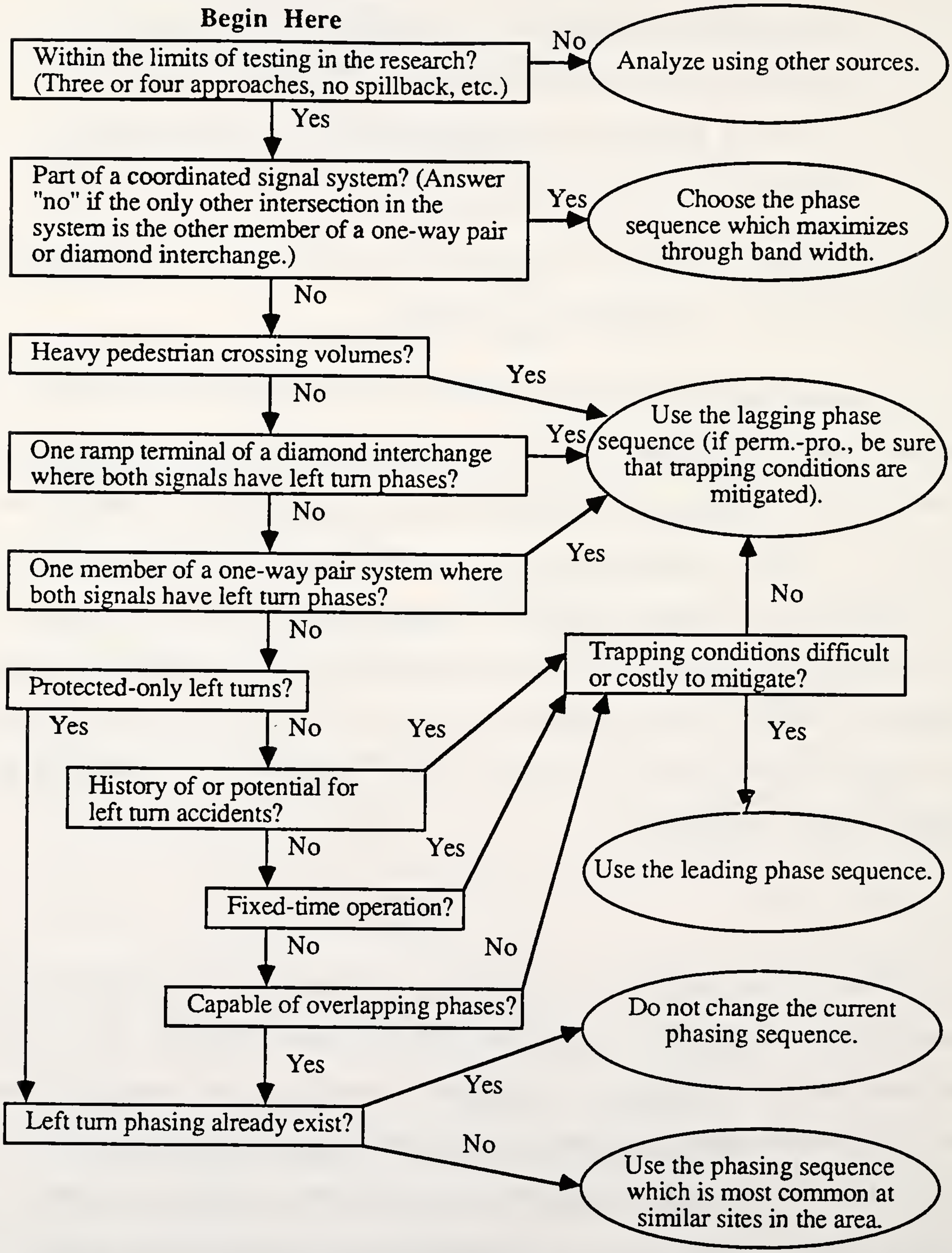


Figure 16. Flowchart for decisions on the phasing sequence of individual intersections.

hindered understanding of certain signal indications. The search for an adequate left turn supplemental sign must continue.

A major trend that emerged from the simulation experiments was that permissive signals consistently meant less vehicle delay and fewer stops than other signals, while protected signals meant more delay and stops than other signals. This result is in line with many previous studies of left turn signals. The simulation results also provided extensive data on the magnitude of the differences in delay caused by the various schemes at different types of intersections. These data would be useful to engineers trying to decide between rival signal schemes when there is no clearly superior scheme.

Future Work

There remain several aspects of the leading and lagging issue that deserve attention. Foremost on the agenda of future work should be a before-and-after field test of the guidelines developed during this research using both safety and delay-related measures of effectiveness. A continuous effort over a period of several years is needed to conduct a proper evaluation.

Another area deserving future effort is the simulation of the utilization of the various signal phases. This portion of the research yielded interested results, but the data collection method was cumbersome limiting the amount of data which could be collected. In addition, the question of whether it is better policy to encourage left turns on the green ball signal or at the end of the signal cycle should be explored. A comprehensive examination of the utilization of signal phases which included alterations to NETSIM or some other traffic simulation model, a thorough validation of the improved model, an experiment comparing phasing alternatives, and a field and/or accident data

collection effort sufficient to convert the simulation results into an estimate of accident reductions would be a step forward for the traffic community.

Another useful extension of this study would be a series of experiments similar to those conducted in Chapter 6 with more varied volume levels. Modelling volumes typical of saturated conditions or typical of the middle of the night may yield some interesting data which could be used to extend the scope of the guidelines for leading and lagging left turn signal phasing.

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APPENDIX A - CODED DATA

Table A1. Motorist survey data.

FIELD NUMBERS:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
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Table A1, continued.

FIELD NUMBERS:

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Table A1, continued.

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Table A1, continued.

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Table A1, continued.

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Table A1, continued.

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Table A1, continued.

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Table A1, continued.

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1	2	2	1	2	3	4	2	1	4	4	3	2	4	1	3	3	9	9	5	3	9	9	9	7	9	9	5	1	7	9	9	10.0	31	2	4
1	2	2	1	3	1	4	3	1	4	1	3	3	2	1	3	5	9	9	5	3	9	9	3	5	9	9	3	1	5	9	9	10.0	13	2	4
4	1	2	1	1	1	4	2	2	4	1	3	2	1	1	3	3	9	9	5	3	9	9	3	3	9	9	5	1	5	9	9	08.0	54	3	4
4	2	2	2	2	2	4	2	1	4	1	2	2	1	1	3	3	9	9	5	3	9	9	9	7	9	9	3	9	7	9	9	00.1	71	1	4
4	1	2	2	2	1	4	3	1	4	1	2	3	1	1	3	1	9	9	5	3	9	9	3	3	9	9	5	1	1	9	9	20.0	01	3	4
4	1	2	2	1	2	4	2	1	4	1	1	2	1	1	3	3	9	9	5	3	9	9	3	3	9	9	3	9	7	9	9	10.0	49	3	4
4	2	2	1	1	3	3	2	1	4	1	1	3	1	1	3	1	9	9	5	3	9	9	3	3	9	9	5	9	7	9	9	10.0	49	2	4
4	1	2	2	3	3	4	2	1	4	1	2	2	1	2	3	3	9	9	5	3	9	9	5	3	9	9	3	1	5	9	9	04.0	38	1	4
4	2	2	2	3	2	4	2	1	3	2	1	2	1	2	3	1	9	9	5	3	9	9	3	2	9	9	5	9	7	9	9	08.0	79	5	4
4	1	2	2	2	3	4	2	1	4	1	1	2	1	2	3	2	9	9	5	2	9	9	5	2	9	9	3	1	5	9	9	17.0	10	2	4
4	2	2	2	3	1	3	3	2	4	2	2	4	1	1	3	1	9	9	5	1	9	9	5	3	9	9	5	1	2	9	9	10.0	07	3	4
2	1	2	2	1	1	4	3	1	4	1	1	3	1	1	3	3	9	9	5	3	9	9	3	3	9	9	3	1	7	9	9	40.0	13	3	4
4	2	2	1	2	2	4	1	1	4	1	1	1	1	1	3	3	9	9	0	3	9	9	3	3	9	9	5	1	5	9	9	10.0	82	3	4
4	1	2	1	2	1	4	2	2	4	2	3	4	2	1	3	3	9	9	5	3	9	9	3	3	9	9	3	1	7	9	9	07.0	09	3	4
4	1	2	1	1	2	4	2	1	4	2	1	2	1	1	3	3	9	9	0	3	9	9	3	3	9	9	5	1	1	9	9	25.0	01	3	4
4	2	2	1	1	3	4	3	1	4	2	1	3	2	1	3	1	9	9	5	7	9	9	3	3	9	9	3	1	1	9	9	08.0	12	4	4
4	2	2	2	3	3	4	2	1	4	1	2	3	2	1	3	7	9	9	9	7	9	9	5	5	9	9	5	1	2	9	9	10.0	43	1	4
4	2	2	1	3	2	4	2	2	4	2	2	2	2	2	3	3	9	9	5	3	9	9	3	3	9	9	3	1	7	9	9	15.0	71	3	4
4	1	2	2	2	3	4	2	1	4	1	1	2	2	2	3	1	9	9	5	6	9	9	3	3	9	9	5	9	7	9	9	40.0	37	3	4
4	2	2	1	3	1	4	1	4	1	1	1	4	1	3	3	3	9	9	5	3	9	9	3	1	3	9	3	2	2	9	9	10.0	17	2	4
1	1	2	2	1	1	4	2	1	4	1	1	2	1	1	3	5	9	9	5	5	9	9	3	3	9	9	3	9	4	9	9	20.0	03	2	3
1	1	2	2	2	2	4	3	1	4	3	1	2	3	1	3	3	9	9	5	8	9	9	3	3	9	9	5	1	5	9	9	14.0	18	5	3
2	2	2	2	2	1	4	3	1	4	1	1	3	1	1	3	2	9	9	5	2	9	9	5	2	9	9	3	1	3	5	9	17.0	49	2	3
1	1	2	2	1	2	4	2	1	4	1	1	2	1	1	3	1	9	9	5	3	9	9	3	3	9	9	5	1	5	9	9	07.0	52	2	4
1	1	2	1	1	3	3	2	1	4	1	1	2	1	1	3	1	9	9	5	5	9	9	3	3	9	9	3	1	1	9	9	12.0	48	3	4
1	2	2	2	3	3	4	2	1	4	3	1	4	2	1	3	3	9	9	5	3	9	9	9	5	9	9	5	1	7	9	9	35.0	37	3	4
1	1	2	2	3	2	4	3	2	4	2	1	3	3	1	3	1	3	9	5	1	3	9	3	3	9	9	3	1	1	2	9	10.0	43	2	4
1	2	2	1	2	3	4	3	4	1	4	3	2	2	1	3	1	9	9	5	1	9	9	3	3	9	9	5	1	1	9	9	15.0	74	2	4
1	1	2	2	3	1	1	3	2	4	2	1	3	2	1	3	1	3	9	0	3	9	9	3	3	9	9	3	1	2	9	9	15.0	06	6	4
2	2	2	1	1	1	4	3	1	4	1	1	3	2	2	3	3	9	9	5	2	3	9	3	3	9	9	3	2	3	9	9	06.0	34	3	4
2	2	2	2	2	2	2	2	1	4	1	2	2	2	1	3	3	9	9	9	7	9	9	3	3	9	9	5	1	2	3	9	02.0	62	1	4
2	2	2	1	2	1	4	2	1	4	1	1	3	2	3	3	3	9	9	5	7	9	9	3	3	9	9	3	9	7	9	9	05.0	34	1	4
4	1	2	2	1	2	4	3	1	4	1	1	1	1	2	3	1	9	9	5	1	9	9	5	3	1	9	5	9	7	9	9	14.0	31	1	4
4	2	2	1	1	3	4	3	1	4	1	1	3	3	1	3	8	9	9	5	3	9	9	3	3	9	9	3	1	1	9	9	18.0	32	3	4
4	2	2	2	3	3	4	3	4	1	1	1	2	1	3	3	3	9	9	5	3	9	9	3	3	9	9	5	9	7	9	9	12.0	34	1	4
4	2	2	2	3	2	4	2	2	4	2	3	3	2	1	3	3	9	9	5	3	9	9	3	3	9	9	3	1	3	9	9	09.0	87	3	4
4	2	2	2	2	3	4	2	1	4	1	3	1	2	1	3	7	9	9	5	3	9	9	3	3	9	9	5	1	7	9	9	12.0	49	2	4
4	1	2	2	3	1	2	1	1	3	4	1	4	4	1	3	3	9	9	5	3	9	9	5	3	9	9	3	9	7	9	9	15.0	08	1	4

FIELD KEY:

FIELD	COLUMNS	VARIABLE AND UNITS	LEVELS
1	1	INTERVIEWER NUMBER	
2	3	RESPONDENT SEX	1=MALE, 2=FEMALE
3	5	ANSWER TO QUESTION 1.A.	1=NO, 2=YES
4	7	ANSWER TO QUESTION 1.B.	1=NO, 2=YES
5	9	PROTECTED SIGN TYPE	1=NONE, 2="LEFT TURN ON ARROW ONLY," 3="LEFT TURN SIGNAL"
6	11	PROTECTED-PERMISSIVE SIGN TYPE	1=NONE, 2="LEFT TURN ON GREEN OR ARROW," 3="LEFT TURN YIELD ON GREEN ●"

Table A1, continued.

7	13	ANSWER TO QUESTION 2.A.	CODES PROVIDED IN TABLE 1
8	15	ANSWER TO QUESTION 2.B.	CODES PROVIDED IN TABLE 1
9	17	ANSWER TO QUESTION 2.C.	CODES PROVIDED IN TABLE 1
10	19	ANSWER TO QUESTION 2.D.	CODES PROVIDED IN TABLE 1
11	21	ANSWER TO QUESTION 2.E.	CODES PROVIDED IN TABLE 1
12	23	ANSWER TO QUESTION 2.F.	CODES PROVIDED IN TABLE 1
13	25	ANSWER TO QUESTION 2.G.	CODES PROVIDED IN TABLE 1
14	27	ANSWER TO QUESTION 2.H.	CODES PROVIDED IN TABLE 1
15	29	ANSWER TO QUESTION 3	1=CORRECT, 2=UNSURE, 3=WRONG
16	31	ANSWER TO QUESTION 4.A.	0=PERMISSIVE, 3=PROTECTED, 9=NO PREFERENCE
17	33	1ST ANSWER TO QUESTION 4.B.	1=SAFER, 2=LESS DELAY, 3=LESS CONFUSION, 4=DON'T LIKE CHANGES, 5=MORE LIKE NORMAL, 6=ALL SIGNALS SHOULD LOOK ALIKE, 7=UNSURE, 8=OTHER, 9=NO REASON
18	35	2ND ANSWER TO QUESTION 4.B.	SAME AS LEVELS FOR FIELD 17
19	37	3RD ANSWER TO QUESTION 4.B.	SAME AS LEVELS FOR FIELD 17
20	39	ANSWER TO QUESTION 5.A.	0=PERMISSIVE, 5=PROTECTED-PERMISSIVE, 9=NO PREFERENCE
21	41	1ST ANSWER TO QUESTION 5.B.	SAME AS LEVELS FOR FIELD 17
22	43	2ND ANSWER TO QUESTION 5.B.	SAME AS LEVELS FOR FIELD 17
23	45	3RD ANSWER TO QUESTION 5.B.	SAME AS LEVELS FOR FIELD 17
24	47	ANSWER TO QUESTION 6.A.	3=PROTECTED, 5=PROTECTED-PERMISSIVE, 9=NO PREFERENCE
25	49	1ST ANSWER TO QUESTION 6.B.	SAME AS LEVELS FOR FIELD 17
26	51	2ND ANSWER TO QUESTION 6.B.	SAME AS LEVELS FOR FIELD 17
27	53	3RD ANSWER TO QUESTION 6.B.	SAME AS LEVELS FOR FIELD 17
28	55	SIGNAL TYPE SHOWN DURING QUESTION 7	3=PROTECTED, 5=PROTECTED-PERMISSIVE
29	57	ANSWER TO QUESTION 7.A.	1=BEFORE, 2=AFTER, 9=NO PREF.
30	59	1ST ANSWER TO QUESTION 7.B.	SAME AS LEVELS FOR FIELD 17
31	61	2ND ANSWER TO QUESTION 7.B.	SAME AS LEVELS FOR FIELD 17
32	63	3RD ANSWER TO QUESTION 7.B.	SAME AS LEVELS FOR FIELD 17
33	65-68	ANSWER TO QUESTION 8 (000)	
34	70-71	ANSWER TO QUESTION 9	1-92 INDIANA COUNTIES ALPHA-BETICALLY
35	73	ANSWER TO QUESTION 10	1=15-25 YEARS, 2=26-35, 3=36-45, 4=46-55, 5=56-65, 6=66 AND OLDER, 7=NO RESPONSE
36	75	DAY OF INTERVIEW	1=AUGUST 17, 2=AUGUST 18, 3=AUGUST 19, 4=AUGUST 20

Table A2. Four-approach intersection simulation data.

FIELD NUMBERS:

123456	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
111111	60	61	55	60	211	208	430	432	85	71	43	43	254	289	098	101
111112	60	62	72	71	209	211	431	431	70	67	58	57	257	274	157	164
111113	59	60	71	71	209	210	430	431	56	69	57	60	232	272	166	174
111114	62	58	63	62	211	208	435	431	72	66	48	51	262	232	125	133
111115	61	58	68	65	208	209	430	431	88	68	54	50	262	248	131	131
114111	55	60	55	54	213	215	421	421	58	61	35	32	227	235	081	086
114112	63	56	73	74	219	219	419	421	66	61	43	46	279	242	141	150
114113	57	59	74	73	213	210	425	416	62	63	51	54	235	259	155	162
114114	58	60	65	64	215	216	423	420	64	70	37	38	250	271	107	107
114115	57	61	67	65	212	213	417	418	56	65	44	41	216	261	124	112
113211	62	64	45	55	207	207	475	469	73	75	25	57	291	286	079	148
113212	58	61	74	70	214	214	464	462	84	62	51	56	243	242	169	170
113213	59	60	75	68	212	215	465	464	66	61	60	57	246	231	180	168
113214	61	62	60	48	212	213	466	467	74	70	41	43	249	249	109	120
113215	59	60	62	52	213	214	465	465	67	66	43	45	240	258	108	117
112211	61	59	53	57	214	215	461	464	72	59	36	47	288	228	094	112
112212	60	56	78	72	217	217	459	486	61	60	59	64	237	243	220	208
112213	59	62	74	74	209	210	464	470	67	68	65	68	275	265	215	205
112214	56	59	63	66	217	214	465	465	62	65	41	54	239	243	124	149
112215	61	58	65	61	210	214	467	467	66	67	43	55	254	222	122	142
212111	58	60	20	63	213	212	421	424	62	64	12	46	252	234	076	128
212112	59	55	54	76	213	213	424	421	69	62	31	83	275	229	157	213
212113	63	58	60	74	219	215	422	420	67	56	38	70	259	231	188	211
212114	54	60	36	69	214	211	422	420	57	69	18	56	226	271	109	165
212115	55	60	53	72	217	218	423	418	57	65	30	64	228	260	149	175
213111	60	58	11	62	210	209	433	433	64	65	13	88	254	249	076	238
213112	58	60	45	45	208	207	432	433	71	71	25	52	253	281	130	162
213113	57	60	43	39	209	212	433	432	66	73	25	39	255	258	127	135
213114	64	59	18	42	209	210	432	432	71	73	10	58	284	254	087	145
213115	61	59	19	35	207	207	433	434	73	68	13	48	275	269	089	132
214211	62	59	25	30	212	213	471	472	70	69	21	23	267	269	094	101
214212	58	60	65	67	212	212	464	469	63	69	46	49	224	280	261	270
214213	61	60	70	71	219	215	482	461	63	67	61	64	267	260	291	303
214214	62	61	46	46	213	213	466	472	72	68	30	31	258	248	133	130
214215	58	60	50	51	216	215	469	463	63	69	34	35	224	242	147	156
211211	60	61	64	65	208	206	472	476	66	71	49	52	249	265	132	143
211212	57	55	79	79	208	209	477	476	70	61	76	77	260	223	265	268
211213	64	54	78	77	207	207	478	479	71	67	74	73	293	251	247	234
211214	59	61	69	70	209	208	478	474	65	73	55	61	256	284	164	172
211215	61	61	71	71	207	209	475	469	71	67	60	65	266	258	185	185
211121	60	60	63	60	210	208	633	629	70	69	48	51	258	251	149	145
211122	58	60	70	73	209	204	638	634	66	71	65	65	280	267	228	241
211123	62	61	71	71	211	203	631	630	58	71	71	69	271	275	238	222
211124	61	59	69	66	204	208	634	632	75	64	68	59	296	233	207	193
211125	61	58	70	70	208	210	632	631	69	67	66	70	257	248	220	223
214121	54	60	18	28	212	213	627	635	67	66	13	15	249	259	098	108
214122	58	58	62	60	212	212	624	622	67	62	42	45	250	241	243	239
214123	62	64	62	62	214	214	619	630	70	75	48	48	260	281	262	250
214124	61	63	54	54	212	212	623	627	74	73	36	36	281	277	209	198
214125	54	61	57	58	216	215	619	625	61	67	38	42	217	244	206	224
213221	61	59	09	55	209	209	668	677	70	71	12	87	288	265	095	251
213222	58	58	57	39	211	206	680	678	66	67	44	44	256	241	233	164

Table A2, continued.

FIELD NUMBERS: 123456	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
213223	59	61	58	40	213	215	681	671	66	68	47	42	255	274	247	169
213224	57	63	40	34	209	208	674	680	62	72	26	54	240	275	157	161
213225	59	60	45	34	210	209	678	677	67	67	33	50	253	246	186	161
212221	61	61	28	61	212	212	670	661	70	66	19	53	286	254	110	160
212222	57	61	67	72	214	215	666	657	63	68	57	72	247	255	317	258
212223	60	55	68	72	217	214	655	656	68	63	67	78	251	230	342	273
212224	58	61	55	68	215	212	659	660	62	67	39	65	231	262	215	215
212225	63	54	59	69	215	216	656	657	70	56	46	68	268	233	239	207
112121	55	62	51	55	215	216	612	612	58	67	31	47	215	257	096	131
112122	56	61	70	62	215	214	622	616	58	59	50	58	227	253	180	182
112123	58	58	69	63	212	210	620	617	62	60	52	60	225	229	175	193
112124	60	61	66	60	215	216	620	616	65	60	45	56	252	231	146	167
112125	61	58	68	63	211	214	617	619	71	80	50	54	283	212	188	183
113121	58	57	47	48	207	211	628	627	69	66	23	48	259	243	084	146
113122	58	58	69	63	212	210	620	617	62	60	52	60	225	229	175	193
113123	59	57	65	56	215	215	618	618	66	61	45	42	232	231	141	154
113124	62	58	63	53	212	212	620	620	72	64	30	41	270	255	122	133
113125	62	62	60	52	214	213	619	621	64	67	40	39	252	244	132	138
114221	61	59	58	56	217	216	655	658	65	63	38	37	254	246	131	112
114222	61	63	73	71	217	219	652	653	65	61	65	62	254	247	264	242
114223	58	60	71	73	212	209	651	653	62	71	62	65	223	257	233	231
114224	65	56	69	67	218	218	653	655	67	68	55	54	289	232	187	197
114225	60	58	69	66	213	213	655	660	67	62	54	56	258	244	175	192
111221	61	60	58	56	211	208	673	673	68	70	46	44	288	252	141	137
111222	59	62	67	67	210	208	676	677	69	72	63	64	266	268	273	220
111223	60	58	66	66	209	211	669	674	68	73	87	63	273	250	215	217
111224	63	57	61	64	209	208	670	671	76	61	57	58	287	237	190	185
111225	60	55	68	72	217	214	655	656	68	63	67	78	251	230	342	273
221111	38	34	47	49	216	213	426	425	64	58	43	54	165	155	081	095
221112	40	50	61	63	213	214	428	425	65	72	62	66	169	189	136	145
221113	46	48	64	63	209	211	426	424	65	71	72	65	184	195	154	136
221114	41	38	53	60	209	211	425	425	68	64	56	67	179	164	106	127
221115	44	44	58	59	214	215	424	422	65	64	64	60	173	169	128	124
224111	69	69	22	20	212	215	425	424	85	87	16	16	372	349	083	081
224112	72	72	55	57	219	215	421	424	86	84	39	39	383	352	151	162
224113	72	72	60	61	217	218	422	423	86	83	41	40	370	359	183	184
224114	68	69	39	39	217	219	425	425	78	81	28	28	331	334	103	107
224115	67	68	41	36	220	215	423	424	82	83	27	25	338	335	110	107
223211	67	69	07	45	209	208	477	477	88	83	08	60	328	342	069	155
223212	71	73	61	48	209	208	475	474	92	90	45	30	396	384	173	141
223213	72	73	66	61	216	217	467	468	86	90	49	32	355	378	221	192
223214	70	69	19	26	209	209	482	479	90	85	16	24	380	329	087	099
223215	72	68	17	27	206	207	478	476	97	86	14	19	404	349	084	097
222211	71	69	24	52	215	213	473	468	89	84	16	37	372	343	082	085
222212	71	69	66	76	216	218	465	465	83	85	64	63	332	332	245	203
222213	68	70	68	74	214	214	467	464	84	89	64	62	339	364	254	198
222214	69	68	42	60	216	214	473	466	85	83	32	46	335	336	113	107
222215	72	72	39	60	217	216	470	465	88	88	31	46	398	355	123	115
122111	70	70	54	60	217	218	421	426	80	82	29	41	332	355	071	087
122112	71	70	76	74	217	219	422	424	83	77	50	60	381	319	150	175
122113	71	73	75	74	211	210	425	428	88	88	56	53	376	377	168	152

Table A2, continued.

FIELD NUMBERS:

123456	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
122114	70	69	51	56	213	214	424	430	84	89	34	41	335	349	075	092
122115	72	73	64	59	211	210	426	425	91	90	43	41	397	405	101	097
123111	70	71	51	38	207	205	426	420	84	91	23	32	330	390	062	076
123112	74	72	70	70	216	218	418	420	88	85	50	40	392	335	137	129
123113	69	70	75	74	219	217	420	422	86	85	45	41	368	360	131	132
123114	73	70	54	53	219	216	421	419	89	79	33	27	392	348	073	069
123115	69	70	61	59	215	217	420	418	84	86	35	39	337	367	083	086
124211	71	70	48	53	215	219	466	465	83	81	36	37	355	341	082	082
124212	72	70	77	76	216	216	464	470	84	88	63	65	359	363	198	191
124213	74	72	77	76	209	210	473	473	92	86	64	64	422	351	204	187
124214	72	73	60	61	219	217	465	466	88	87	41	47	349	389	093	108
124215	67	73	61	63	212	209	466	467	82	92	47	46	319	416	116	111
121211	68	64	44	45	212	212	471	470	82	86	33	33	307	304	071	071
121212	59	63	68	68	211	213	489	488	82	81	65	86	282	271	172	182
121213	64	67	68	64	207	211	473	473	87	87	63	58	309	339	171	156
121214	62	63	46	46	218	217	469	468	82	78	33	37	277	261	076	078
121215	64	64	51	53	212	215	467	465	83	80	44	44	284	302	095	095
121121	63	58	35	35	213	213	623	622	85	78	27	28	302	270	081	094
121122	70	68	60	62	212	210	629	629	85	80	47	50	344	323	144	157
121123	68	68	60	59	206	207	632	631	84	88	49	49	331	353	163	150
121124	65	61	41	41	214	213	622	622	81	79	28	31	305	378	083	088
121125	65	67	42	48	210	209	627	627	82	83	33	36	296	320	092	096
124121	70	69	56	57	215	215	622	621	85	83	33	36	347	346	091	103
124122	71	73	68	70	220	218	619	628	83	87	55	55	358	389	193	186
124123	72	69	73	72	211	212	625	627	91	87	54	54	384	385	175	174
124124	72	72	57	57	215	210	624	625	84	87	47	43	368	347	120	113
124125	73	70	65	66	210	210	622	625	92	92	53	48	397	397	149	140
123221	72	73	53	58	208	205	667	661	92	93	30	31	384	374	092	136
123222	71	73	73	67	218	217	665	662	83	86	59	49	357	380	205	169
123223	71	69	73	69	217	215	662	657	87	83	61	48	383	342	219	183
123224	69	67	60	54	215	218	660	658	84	77	48	40	324	300	143	112
123225	70	71	63	55	218	219	858	657	85	84	52	39	346	367	155	111
122221	72	72	56	52	218	215	659	660	87	86	40	40	371	379	125	118
122222	73	72	71	64	218	214	671	667	84	84	66	59	383	370	220	204
122223	71	71	71	67	205	208	671	670	92	87	67	57	384	360	228	211
122224	71	70	66	57	207	214	663	667	91	88	53	47	381	355	164	143
122225	71	71	83	59	210	211	664	667	87	87	58	50	354	353	162	148
222121	71	72	17	60	214	214	628	623	88	88	13	35	387	374	094	099
222122	74	72	59	68	216	217	625	619	90	83	46	54	383	372	211	178
222123	68	72	61	69	218	219	622	612	83	89	46	59	339	389	220	197
222124	70	69	48	54	214	215	624	619	80	83	40	43	320	356	170	120
222125	73	68	51	59	219	216	623	617	87	81	43	45	365	348	186	128
223121	69	88	05	38	210	209	630	641	89	86	06	52	349	338	077	169
223122	67	70	42	30	207	207	635	638	87	82	24	20	344	338	138	130
223123	69	72	51	37	208	207	631	628	87	93	26	18	353	389	168	139
223124	74	72	27	16	208	206	635	636	95	94	19	10	397	398	111	101
223125	73	70	35	15	206	206	633	636	97	88	23	11	389	349	126	094
224221	73	68	38	39	213	215	666	665	89	81	24	23	378	332	132	137
224222	72	70	62	64	217	217	659	653	88	85	57	60	387	385	244	261
224223	71	72	65	66	219	219	662	659	86	89	61	63	384	374	274	282
224224	71	71	53	53	217	215	860	858	84	89	44	47	373	391	191	198

Table A2, continued.

FIELD NUMBERS:

123456	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
224225	66	71	56	55	217	218	664	664	83	84	48	52	322	353	203	213
221221	57	59	57	48	211	212	664	663	79	78	44	46	257	252	111	118
221222	56	53	59	64	212	211	664	661	74	73	70	73	238	237	182	195
221223	53	51	65	65	213	213	667	683	77	76	73	73	227	213	198	199
221224	52	50	57	56	216	213	662	664	64	72	66	68	199	213	155	163
221225	49	53	60	58	213	215	668	664	70	72	69	67	225	207	161	159

FIELD KEY:

FIELD	COLUMNS	VARIABLE AND UNITS	LEVELS
1	1	SP	1=50, 2=30
2	2	FA	1=FIXED, 2=ACTUATED
3	3	P	1=NONE, 2=PERFECT ONE DIR. 3=EARLY, 4=PERFECT BOTH DIRS.
4	4	L	1=140, 2=230
5	5	T	1=600, 2=1000
6	6	S	1=PERMISSIVE, 2=PROTECTED-LAGGING, 3=PROTECTED-LEADING, 4=PERMISSIVE-PROTECTED, 5=PROTECTED-PERMISSIVE
7	8-9	PERCENT STOPPED DELAY, LINK 62,61	
8	11-12	PERCENT STOPPED DELAY, LINK 64,61	
9	14-15	PERCENT STOPPED DELAY, LINK 65,61	
10	17-18	PERCENT STOPPED DELAY, LINK 63,61	
11	20-22	NUMBER OF VEHICLES, LINK 62,61	
12	24-26	NUMBER OF VEHICLES, LINK 64,61	
13	28-30	NUMBER OF VEHICLES, LINK 65,61	
14	32-34	NUMBER OF VEHICLES, LINK 63,61	
15	36-37	STOPS PER VEHICLE, LINK 62,61 (0.01)	
16	39-40	STOPS PER VEHICLE, LINK 64,61 (0.01)	
17	42-43	STOPS PER VEHICLE, LINK 65,61 (0.01)	
18	45-46	STOPS PER VEHICLE, LINK 63,61 (0.01)	
19	48-50	DELAY, SEC/VEH, LINK 62,61 (0.1)	
20	52-54	DELAY, SEC/VEH, LINK 64,61 (0.1)	
21	56-58	DELAY, SEC/VEH, LINK 65,61 (0.1)	
19	60-62	DELAY, SEC/VEH, LINK 63,61 (0.1)	

Table A3. Three-approach intersection simulation data.

FIELD NUMBERS:

1	2	3	4	5	6	7	8	9	10	11	12
1	1	2	1	25	70	12	42	040	087	0273	0255
1	1	1	1	70	69	40	38	077	081	0270	0255
2	2	2	1	37	70	18	39	053	091	0421	0355
2	2	1	1	69	69	49	41	096	092	0414	0352
1	3	4	1	32	18	12	03	050	042	0472	0462
1	3	3	1	69	11	47	03	099	042	0466	0461
2	4	4	1	40	18	18	04	066	046	0615	0551
2	4	3	1	70	13	51	03	122	043	0605	0552
1	2	4	1	30	18	12	03	045	040	0372	0358
1	2	3	1	71	12	45	02	093	035	0367	0359
2	1	4	1	36	28	22	04	048	040	0320	0254
2	1	3	1	70	22	48	04	095	037	0313	0257
1	4	2	1	28	70	11	45	050	106	0577	0548
1	4	1	1	66	66	44	43	095	100	0565	0546
2	3	2	1	29	68	16	45	052	097	0512	0460
2	3	1	1	75	70	53	46	133	100	0512	0457
1	1	4	1	34	10	16	03	042	030	0272	0254
1	1	3	1	70	15	48	03	000	035	0260	0252
1	2	2	1	24	70	11	40	041	089	0373	0355
1	2	1	1	70	65	42	38	094	081	0369	0352
1	3	2	1	23	66	10	42	042	092	0471	0454
1	3	1	1	69	69	44	47	095	111	0486	0455
1	4	4	1	40	16	13	03	060	044	0577	0560
1	4	3	1	71	16	50	03	118	047	0573	0555
2	1	2	1	33	68	18	35	052	074	0319	0253
2	1	1	1	70	70	48	40	093	090	0313	0252
2	2	4	1	38	17	21	03	057	041	0420	0358
2	2	3	1	70	17	49	03	101	040	0414	0353
2	3	4	1	40	18	21	04	066	043	0518	0459
2	3	3	1	72	14	52	03	118	045	0508	0462
2	4	2	1	31	68	17	46	058	107	0616	0546
2	4	1	1	69	67	50	45	117	103	0601	0539
1	1	2	2	21	79	09	60	036	158	0272	0250
1	1	1	2	68	80	35	57	071	152	0270	0254
2	2	2	2	26	78	15	59	050	159	0420	0356
2	2	1	2	72	77	46	54	099	146	0419	0360
1	3	4	2	24	62	10	23	046	123	0474	0459
1	3	3	2	72	62	49	22	112	114	0463	0457
2	4	4	2	29	67	13	30	056	151	0616	0555
2	4	3	2	70	64	49	27	118	139	0605	0549
1	2	4	2	36	58	14	18	047	090	0372	0352
1	2	3	2	69	56	45	17	092	092	0369	0352
2	1	4	2	28	62	17	20	047	104	0316	0253
2	1	3	2	73	64	48	19	105	094	0314	0253
1	4	2	2	19	76	08	64	046	176	0579	0545
1	4	1	2	67	77	48	65	106	178	0565	0546
2	3	2	2	24	78	12	62	049	166	0515	0452
2	3	1	2	68	77	47	64	102	167	0504	0452
1	1	4	2	25	65	14	20	044	092	0272	0250
1	1	3	2	72	81	45	19	094	094	0267	0254
1	2	2	2	28	78	09	59	040	153	0374	0354
1	2	1	2	67	77	40	60	080	153	0365	0355

Table A3, continued.

FIELD NUMBERS:

1	2	3	4	5	6	7	8	9	10	11	12
1	3	2	2	21	77	08	66	043	179	0470	0457
1	3	1	2	69	76	48	58	107	153	0467	0447
1	4	4	2	21	65	08	31	049	180	0582	0547
1	4	3	2	69	65	46	26	108	135	0570	0551
2	1	2	2	23	80	15	58	043	158	0315	0253
2	1	1	2	71	81	43	62	063	168	0316	0250
2	2	4	2	31	84	18	22	051	105	0420	0353
2	2	3	2	70	55	45	18	103	089	0414	0357
2	3	4	2	35	58	18	19	055	103	0515	0458
2	3	3	2	69	56	44	18	103	106	0514	0400
2	4	2	2	30	77	13	62	057	174	0617	0548
2	4	1	2	68	77	50	70	114	181	0806	0541
1	1	2	3	33	80	18	80	043	164	0271	0258
1	1	1	3	71	78	52	56	094	145	0269	0252
2	2	2	3	42	78	20	57	059	152	0424	0359
2	2	1	3	66	78	47	58	088	154	0413	0352
1	3	4	3	27	62	11	21	049	110	0474	0466
1	3	3	3	67	63	47	21	095	116	0462	0455
2	4	4	3	41	64	20	25	072	133	0618	0560
2	4	3	3	65	67	46	30	100	155	0596	0547
1	2	4	3	38	53	14	14	049	083	0373	0361
1	2	3	3	69	65	42	24	086	118	0364	0356
2	1	4	3	38	65	21	23	059	110	0318	0257
2	1	3	3	68	67	50	71	091	102	0314	0254
1	4	2	3	26	77	11	66	053	186	0575	0556
1	4	1	3	68	76	47	68	103	189	0554	0546
2	3	2	3	34	76	19	60	057	158	0517	0463
2	3	1	3	66	77	46	57	093	149	0508	0468
1	1	4	3	32	57	15	16	045	087	0271	0259
1	1	3	3	70	82	49	18	087	088	0270	0251
1	2	2	3	31	78	13	56	044	148	0370	0360
1	2	1	3	67	78	40	58	083	158	0366	0352
1	3	2	3	32	77	13	58	050	157	0476	0464
1	3	1	3	66	78	46	61	091	160	0465	0453
1	4	4	3	34	64	11	27	055	139	0582	0557
1	4	3	3	87	86	47	30	106	155	0568	0550
2	1	2	3	30	78	18	55	042	139	0317	0258
2	1	1	3	65	79	48	57	083	162	0316	0249
2	2	4	3	44	58	22	16	062	090	0421	0361
2	2	3	3	87	80	49	19	095	098	0411	0354
2	3	4	3	41	59	21	20	081	107	0518	0462
2	3	3	3	67	62	49	21	102	115	0508	0461
2	4	2	3	38	76	17	80	059	164	0817	0559
2	4	1	3	68	78	53	70	120	191	0599	0548

FIELD KEY:

FIELD	COLUMNS	VARIABLE AND UNITS	LEVELS
1	1	L	1=140, 2=230
2	3	T	1=400, 2=800, 3=800, 4=1000
3	5	P	1=NONE, 2=LEFT DIRECTION, 3=OPPOSITE DIRECTION. 4=BOTH DIRECTIONS
4	7	S	1=PERMISSIVE, 2=PERMISSIVE-PROTECTED, 3-PROTECTED-PERM.
5	9-10	PERCENT STOP DELAY, LEFT DIRECTION	
6	12-13	PERCENT STOP DELAY, OPPOSITE DIRECTION	
7	15-16	STOPS PER VEHICLE, LEFT DIR. (0.01)	
8	18-19	STOPS PER VEHICLE, OPPOSITE DIRECTION (0.01)	
9	21-23	DELAY, SEC/VEH, LEFT DIRECTION (0.1)	
10	25-27	DELAY, SEC/VEH, OPPOSITE DIRECTION (0.1)	
11	29-32	NUMBER OF VEHICLES IN LEFT DIRECTION	
12	34-37	NUMBER OF VEHICLES IN OPPOSITE DIRECTION	

Table A4. Diamond interchange simulation data.

FIELD NUMBERS:

12345	6 7 8 910111213	14 15 16 17	1819202122232425	26 27 28 29 30 31 32 33
21214	9024882255541106	294490297493	4828462989681715	1981121911122592382262239
12213	8644874052580303	488694499703	5333476367680806	1981441731842292780830 91
12111	7433693158540403	505709507710	4626462973720705	074118070113271259119108
11124	8028813160600402	300496299499	3622412685840906	062101072106288287122137
11122	8736863963590406	298493301495	6228592781810305	163136142132327273058063
11121	8031802658580302	296493298495	4124402084820705	064111069095279273130124
22111	7354704561601404	502699504699	3639373679822009	056172061138305305168164
21111	7643743856550402	306505302504	3239373876770810	055140055133272264274251
11111	8030803452520202	305508307509	4233393170720506	075120074121248245175113
22212	8922892463610917	482681488689	8623832579751216	409125377127328291163146
11213	9150894452530704	293499296507	3750445971680508	151173187176263242064126
21213	9249914049500017	292503294510	7066736488680029	348217359190230234042186
11112	8629863054530104	305508308510	5426652472700204	150121170132247252073065
11113	8746884449510102	305500305488	6449888389650204	168183179196231241113079
11114	8022802152500103	304508304508	4623452470870304	094102098103251237108133
11115	8532854149500305	305497297497	5227575668700512	122121144185235241094198
11123	8654875957570200	294489300502	6249635981800100	146215159232275277048071
11125	8341824057570502	300504302498	5446494585841005	117152101143279277153123
11211	3733033652491203	296494295490	0431023165601607	010099005097239223148157
11212	9028912959570707	291487292489	3722322271671309	160111138105288270103094
11214	7920752551530404	291490292492	1620092363611211	054084034082235240227140
11215	7640763954510403	294501302498	1827174672670707	062108063124265230145137
11221	5942575161610205	295500293497	0628053083820511	017103013123286309136182
11222	9139913963601310	301494294492	5030503485831209	197135194130318285084101
11223	9252895358590001	297495293501	4849494985820003	184192179194279276044049
11224	8640873958600506	294494293496	2233243080790913	058111068110286288128198
11225	8647894058600804	295492301496	2243254484821714	063134072123289294139196
21112	8931893255590308	304504305506	8235773772740406	257146243149254301098094
21113	9048893749500512	304496306485	8465826667700412	295211277201227233109114
21114	8521862755550301	304506305506	6427682872720403	182117178126249255132132
21115	8742884346531106	304496307489	6757706666741507	187179212206218266135110
21121	8237783961610802	305507303505	3837353786861609	067124058126313314222156
21122	8843914461590402	300495301497	7651774784840202	235184263179299295100103
21123	8957906056560106	300499293511	7458788685840305	223247253255283269096100
21124	8537844155550404	301491300497	6139534781801013	147139114156260255182185
21125	8541874758571007	292492301498	6056616381832217	148170150182265271184172
21211	1137154353610606	297493294498	0330033671751713	008104012116249294214252
21212	9234922952550812	292488291490	6737703567690912	344148366143236258180182
21215	9046914551530708	294498296506	5061466869691019	227182179188237253119198
21221	5153325265612607	289489298495	0539043687843520	011132013131334292271343
21222	9243924759581513	300500300491	7248754684841916	352176343184287277172177
21223	9261916058590214	298501298508	7856756787840205	352247337256287287076057
21224	8940914155561505	301497302497	5144564782801912	182147202151261263195188
21225	9141874557580810	299496300504	5648586282831724	219156208172272281156297
12112	8318822265600301	507699508703	6713671579780302	160106157114340292075076
12113	8443854154551117	504703500688	6832757176741013	179153196210257259130110
12114	7921801955580103	504704503709	5818591971780306	120107125105266278111105
12115	8033844246510501	506695493690	6024666664671003	135128158191210240105084
12121	7537703661640317	493687493688	4324452681850614	078119081122295325107160
12122	8532862665630101	494695489696	7125762584850100	192128198123348304063064
12123	8549834957600903	490698503683	7041726780860602	176189185234272287078056
12124	8030803166640308	498685489690	5724622683840511	119120135123323316106094

Table A4, continued.

FIELD NUMBERS:

12345	6 7 8 910111213	14 15 16 17	1819202122232425	26 27 28 29 30 31 32 33
12125	8438824661620206	487688500706	7238596184850312	175159131193295305120136
12211	3849554657610410	491684493691	0738103871720509	018126027119271298148123
12212	8519851962590512	487689485689	5111511176730609	185095197097310269093106
12214	8130822458590904	482888487688	3420332070711711	118106108093281281169172
12215	8236834153560402	486682502697	3625335866700505	116118108172237265187141
12221	6952725184850308	491688494690	1932163788840310	058133034133324324142087
12222	8827883065631705	489891496693	5722582281841506	206111215118318308102094
12223	8851875358820206	486680494702	6142598681850103	221189211229285305038045
12224	8437853665630308	494695487893	4628462685810615	143121151111331294147126
12225	8540834457670901	492687498700	5037425383861504	187150133188273313145128
22112	9126912661640813	509705506702	8623902581600911	332129332131306355096098
22113	9147913354541814	517705508683	8649936471731815	297195350201255257157125
22114	8817881658560205	508704503698	8319811974730203	268113248114273281113109
22115	9040894651550818	507696509686	8649847869681017	293173258247229258132108
22121	7760717265670810	498687494682	4536494485862023	075202079322329362281229
22122	9039923964630509	489688486684	8838913985840308	301165387171323309112128
22123	9160905457580310	487889500699	8751886982830207	326251315271270289113100
22124	8638874063600216	488692488666	7538844082800318	205159226166315293176137
22125	8544854957600815	492688487700	7247776685791417	195179218212268292148180
22211	2469278260610409	491889490684	0844055677780917	018203011442282302192175
22213	9147913556563409	483696485710	9052876876721913	467201419194266264127158
22214	8817881760571112	485685488689	7618741974741614	327116334113282272181185
22215	8845884552561609	484697491710	7352757568681516	292180304222238284147149
22222	9138923765641713	491690477679	8239883887831713	381163421161322321158137
22223	9159925457601111	488690490708	8247677479820404	373242400268271285054050
22224	8939894260601805	495888494688	7740694278812312	308164267155290289233192
22225	9051895258581818	487698486708	7649817282792121	321194338242271276157159
22221	4582518565650909	491681492679	0829073909091921	038470023870325334199238

FIELD KEY:

FIELD	COLUMNS	VARIABLE AND UNITS	LEVELS
1	1	L	1=200, 2=400
2	2	T	1=800, 2=1000
3	3	P	1=NONE, 2=BOTH DIRECTIONS
4	4	FA	1=FIXED, 2=ACTUATED
5	5	S	1=PERMISSIVE, 2=PROTECTED-LAGGING, 3=PROTECTED-LEADING, 4=PERMISSIVE-PROTECTED, 5=PROTECTED-PERMISSIVE
6	7-8	PERCENT STOPPED DELAY, LINK 95,61	
7	9-10	PERCENT STOPPED DELAY, LINK 61,86	
8	11-12	PERCENT STOPPED DELAY, LINK 93,86	
9	13-14	PERCENT STOPPED DELAY, LINK 86,81	
10	15-16	PERCENT STOPPED DELAY, LINK	

Table A4, continued.

		82,61
11	17-18	PERCENT STOPPED DELAY, LINK 84,86
12	19-20	PERCENT STOPPED DELAY, LINK 95,91
13	21-22	PERCENT STOPPED DELAY, LINK 93,96
14	24-26	NUMBER OF VEHICLES, LINK 95,61
15	27-29	NUMBER OF VEHICLES, LINK 61,66
16	30-32	NUMBER OF VEHICLES, LINK 93,66
17	33-35	NUMBER OF VEHICLES, LINK 81,86
18	37-38	STOPS PER VEHICLE, LINK 95,61 (0.01)
19	39-40	STOPS PER VEHICLE, LINK 61,66 (0.01)
20	41-42	STOPS PER VEHICLE, LINK 93,66 (0.01)
21	43-44	STOPS PER VEHICLE, LINK 66,61 (0.01)
22	45-46	STOPS PER VEHICLE, LINK 82,61 (0.01)
23	47-48	STOPS PER VEHICLE, LINK 84,66 (0.01)
24	49-50	STOPS PER VEHICLE, LINK 95,91 (0.01)
25	51-52	STOPS PER VEHICLE, LINK 93,96 (0.01)
26	54-56	DELAY, SEC/VEH, LINK 95,81 (0.1)
27	57-59	DELAY, SEC/VEH, LINK 61,86 (0.1)
28	60-62	DELAY, SEC/VEH, LINK 93,66 (0.1)
29	63-65	DELAY, SEC/VEH, LINK 86,61 (0.1)
30	66-68	DELAY, SEC/VEH, LINK 82,61 (0.1)
31	69-71	DELAY, SEC/VEH, LINK 84,81 (0.1)
32	72-74	DELAY, SEC/VEH, LINK 95,91 (0.1)
33	75-77	DELAY, SEC/VEH, LINK 93,96 (0.1)

Table A5. Utilization of signal phases simulation data.

FIELD NUMBERS:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
2	4	2	2	2	06	39	28	18	34	125	57	57	440	443	42	42	227	216
1	3	2	2	2	10	38	28	18	25	117	67	53	442	444	51	48	185	173
1	2	2	2	2	23	29	32	21	12	117	70	64	444	442	52	64	182	205
2	1	2	2	2	27	23	36	23	11	120	70	70	436	442	70	72	232	227
1	4	1	2	2	11	23	21	10	07	072	68	69	417	416	56	50	207	175
2	3	1	2	2	23	32	04	01	13	073	39	30	415	417	25	52	142	155
2	2	1	2	2	09	22	17	15	11	074	57	70	413	417	37	63	209	214
1	1	1	2	2	16	20	19	15	08	078	61	66	416	417	59	59	196	185
1	4	2	1	2	24	29	26	19	18	118	71	74	312	313	47	50	143	143
2	3	2	1	2	53	19	16	14	14	116	34	43	315	313	22	55	104	148
2	2	2	1	2	31	31	23	19	21	125	46	73	312	312	29	61	130	168
1	1	2	1	2	29	01	24	37	37	128	73	71	313	313	72	69	201	203
2	4	1	1	2	18	33	08	05	09	073	50	45	279	281	29	23	140	122
1	3	1	1	2	23	18	13	09	06	076	68	57	283	284	42	47	127	132
1	2	1	1	2	17	28	19	00	07	072	69	70	284	284	40	59	120	162
2	1	1	1	2	29	09	19	18	01	076	73	74	283	282	82	64	190	189
1	4	2	2	1	23	36	45	13	07	124	69	67	449	443	55	56	219	220
2	3	2	2	1	22	46	47	09	01	125	42	35	442	443	27	51	150	172
2	2	2	2	1	26	32	45	11	08	120	57	70	444	440	38	70	219	228
1	1	2	2	1	40	36	32	07	05	120	61	64	442	442	63	62	206	211
2	4	1	2	1	06	33	28	06	00	071	55	58	418	416	32	37	193	212
1	3	1	2	1	16	35	16	03	04	074	61	54	418	416	41	44	160	146
1	2	1	2	1	23	23	19	09	01	075	69	63	421	418	48	56	178	185
2	1	1	2	1	26	24	14	07	03	074	67	71	417	420	56	65	189	208
2	4	2	1	1	24	39	39	12	04	118	41	47	315	314	28	26	132	132
1	3	2	1	1	54	26	21	10	04	128	64	54	314	313	42	47	123	144
1	2	2	1	1	54	34	24	06	04	122	66	70	315	312	45	60	152	181
2	1	2	1	1	57	23	24	13	04	121	71	72	313	313	58	62	167	180
1	4	1	1	1	25	28	13	08	02	078	65	68	284	284	38	39	114	123
2	3	1	1	1	58	17	03	02	00	080	30	41	285	282	22	58	102	159
2	2	1	1	1	36	22	15	06	02	081	49	72	282	283	23	60	130	173
1	1	1	1	1	38	15	13	05	03	074	68	68	283	281	55	55	155	165
2	2	1	1	1	24	25	15	05	02	071	42	73	277	285	18	60	107	184
1	1	2	2	1	31	37	40	08	09	125	63	66	444	445	58	62	194	204
1	4	2	1	2	24	32	27	23	15	111	71	66	315	310	50	48	149	138
2	3	1	2	2	18	33	02	11	11	075	33	29	416	415	20	44	125	148

FIELD KEY:

FIELD	COLUMNS	VARIABLE AND UNITS	LEVELS
1	1	SP	1=50, 2=30
2	3	P	1=NONE, 2=PERFECT ONE DIR., 3=EARLY, 4=PERFECT BOTH DIRS.
3	5	L	1=140, 2=230
4	7	T	1=600, 2=1000
5	9	S	1=PERMISSIVE-PROTECTED, 2=PROTECTED-PERMISSIVE
6	11-12	NUMBER OF LEFT TURNS ON GREEN BALL INDICATION	
7	14-15	NUMBER OF LEFT TURNS ON YELLOW BALL INDICATION	
8	17-18	NUMBER OF LEFT TURNS ON GREEN ARROW INDICATION	
9	20-21	NUMBER OF LEFT TURNS ON YELLOW ARROW INDICATION	
10	23-24	NUMBER OF LEFT TURNS ON RED INDICATION	
11	26-28	TOTAL NUMBER OF LEFT TURNS	
12	30-31	PERCENT STOPPED DELAY, LINK 85,61	
13	33-34	PERCENT STOPPED DELAY, LINK 83,61	
14	36-38	NUMBER OF VEHICLES, LINK 85,61	
15	40-42	NUMBER OF VEHICLES, LINK 83,61	
16	44-45	STOPS PER VEHICLE, LINK 85,61 (0.01)	
17	47-48	STOPS PER VEHICLE, LINK 83,61 (0.01)	
18	50-52	DELAY, SEC/VEH, LINK 85,61 (0.1)	
19	54-56	DELAY, SEC/VEH, LINK 83,61 (0.1)	

Table A6. Real intersection simulation data.

FIELD NUMBERS:

1	2	3	4	5
1	1	1	07.5	.46
1	1	2	09.0	.52
1	2	1	05.3	.27
1	2	2	06.9	.37
1	3	1	08.3	.36
1	3	2	08.3	.39
1	4	1	05.8	.31
1	4	2	05.3	.31
1	5	1	03.2	.14
1	5	2	04.4	.21
2	1	1	24.0	.70
2	1	2	20.4	.74
2	2	1	15.9	.45
2	2	2	24.7	.77
2	3	1	17.9	.49
2	3	2	22.2	.74
2	4	1	15.9	.47
2	4	2	23.4	.76
2	5	1	14.3	.43
2	5	2	19.9	.65
3	1	1	16.9	.64
3	1	2	21.8	.73
3	2	1	13.1	.51
3	2	2	20.6	.69
3	3	1	13.2	.51
3	3	2	21.0	.71
3	4	1	12.6	.47
3	4	2	18.8	.66
3	5	1	12.5	.46
3	5	2	20.8	.70

FIELD NUMBERS:

1	2	3	4	5
1	1	1	08.0	.46
1	1	2	08.8	.48
1	2	1	05.7	.27
1	2	2	05.9	.30
1	3	1	08.2	.35
1	3	2	09.0	.43
1	4	1	05.5	.29
1	4	2	05.3	.28
1	5	1	02.8	.14
1	5	2	02.8	.13
2	1	1	24.4	.72
2	1	2	20.5	.72
2	2	1	15.9	.44
2	2	2	23.3	.75
2	3	1	15.6	.45
2	3	2	25.2	.76
2	4	1	16.0	.45
2	4	2	23.4	.74
2	5	1	15.8	.43
2	5	2	20.5	.63
3	1	1	17.2	.65
3	1	2	23.3	.74
3	2	1	13.3	.51
3	2	2	20.0	.68
3	3	1	13.2	.50
3	3	2	20.7	.70
3	4	1	12.8	.50
3	4	2	18.9	.63
3	5	1	10.4	.40
3	5	2	19.4	.65

FIELD KEY:

FIELD	COLUMNS	VARIABLE AND UNITS	LEVELS
1	1	I	1=86TH AT SB I-465 RAMP, 2=SOUTH AT DELAWARE, 3=OHIO AT DELAWARE
2	3	H	1=MORNING PEAK, 2=MIDDAY, 3=EVENING PEAK, 4=OTHER HOURS, 5=OVERNIGHT
3	5	S	1=PERMISSIVE-PROTECTED, 2=PROTECTED-PERMISSIVE
4	7-10	DELAY, SEC/VEH, AVERAGE OF LEFT AND OPPOSITE DIRECTIONS WEIGHTED BY NUMBER OF VEHICLES	
5	12-14	STOPS PER VEHICLE, AVERAGE OF LEFT AND OPPOSITE DIRECTIONS WEIGHTED BY NUMBER OF VEHICLES	

APPENDIX B - UTILIZATION OF SIGNAL PHASES RESULTS

Table B1. ANOVA results for percent of left turns on the green ball for the utilization of signal phases experiment.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
MODEL	25	0.65281701	0.02610488
ERROR	10	0.01664913	0.00166491
CORRECTED TOTAL	35	0.66926615	

SOURCE	DF	TYPE I SS	F VALUE	PR > F
SP	1	0.00420815	2.53	0.1430
L	1	0.02473502	14.86	0.0032
T	1	0.21490013	129.08	0.0001
P	3	0.15606262	31.25	0.0001
S	1	0.08383107	50.35	0.0001
SP*L	1	0.00240182	1.44	0.2574
SP*T	1	0.00522506	3.14	0.1069
SP*P	3	0.05918813	11.85	0.0012
SP*S	1	0.00545084	3.27	0.1005
L*T	1	0.00155721	0.94	0.3563
L*P	3	0.01593871	3.19	0.0713
L*S	1	0.00160063	0.96	0.3500
T*P	3	0.04988908	9.99	0.0024
T*S	1	0.01095268	6.58	0.0281
P*S	3	0.01667488	3.34	0.0643

F VALUE	PR > F	R-SQUARE	C.V.
15.68	0.0001	0.975123	14.4052
	ROOT MSE		PGB MEAN
	0.04080335		0.28325512

DF	TYPE III SS	F VALUE	PR > F
1	0.00157201	0.94	0.3541
1	0.02196879	13.20	0.0046
1	0.25293509	151.92	0.0001
3	0.13843979	27.72	0.0001
1	0.08621172	51.78	0.0001
1	0.00187130	1.12	0.3140
1	0.00770414	4.63	0.0570
3	0.05945675	11.90	0.0012
1	0.00521191	3.13	0.1073
1	0.00149095	0.90	0.3663
3	0.01840054	3.68	0.0508
1	0.00142756	0.86	0.3763
3	0.05351806	10.71	0.0018
1	0.01158648	6.96	0.0248
3	0.01667488	3.34	0.0643

Table B2. ANOVA results for percent of left turns on the yellow ball for the utilization of signal phases experiment.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	25	0.31989270	0.01279571	7.90	0.0009	0.951784	13.8891
ERROR	10	0.01620525	0.00162053		ROOT MSE		PYB MEAN
CORRECTED TOTAL	35	0.33609795			0.04025575		0.29407180

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
SP	1	0.00246297	1.52	0.2458	1	0.00054180	0.33	0.5759
L	1	0.04622709	28.53	0.0003	1	0.04406245	27.19	0.0004
T	1	0.04330199	26.72	0.0004	1	0.03924039	24.21	0.0006
P	3	0.09780168	20.12	0.0001	3	0.11157089	22.95	0.0001
S	1	0.01506163	9.29	0.0123	1	0.01393509	8.60	0.0150
SP*L	1	0.00034075	0.21	0.6564	1	0.00000027	0.00	0.9899
SP*T	1	0.00102041	0.63	0.4459	1	0.00137985	0.85	0.3779
SP*P	3	0.01285095	2.64	0.1068	3	0.01569878	3.23	0.0694
SP*S	1	0.00202089	1.25	0.2902	1	0.00090796	0.56	0.4714
L*T	1	0.00006681	0.04	0.8432	1	0.00009870	0.06	0.8101
L*P	3	0.00287617	0.59	0.6345	3	0.00222975	0.46	0.7172
L*S	1	0.00619703	3.82	0.0790	1	0.00535738	3.31	0.0991
T*P	3	0.07308183	15.03	0.0005	3	0.07205249	14.82	0.0005
T*S	1	0.00092984	0.57	0.4662	1	0.00053498	0.33	0.5783
P*S	3	0.01565268	3.22	0.0698	3	0.01565268	3.22	0.0698

Table B3. ANOVA results for percent of left turns on the green arrow for the utilization of signal phases experiment.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	25	0.23758647	0.00950346	3.58	0.0199	0.899430	22.9817
ERROR	10	0.02656578	0.00265658		ROOT MSE		PGA MEAN
CORRECTED TOTAL	35	0.26415224			0.05154200		0.22427429

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
SP	1	0.00700187	2.64	0.1356	1	0.00221371	0.83	0.3828
L	1	0.03558936	13.40	0.0044	1	0.02942705	11.08	0.0076
T	1	0.03633299	13.68	0.0041	1	0.05011663	18.87	0.0015
P	3	0.05123310	6.43	0.0106	3	0.03876593	4.87	0.0244
S	1	0.01399450	5.27	0.0446	1	0.01044530	3.93	0.0755
SP*L	1	0.01180060	4.44	0.0613	1	0.00759828	2.86	0.1217
SP*T	1	0.00001067	0.00	0.9507	1	0.00010855	0.04	0.8439
SP*P	3	0.00890262	1.12	0.3877	3	0.00526262	0.66	0.5950
SP*S	1	0.01508873	5.68	0.0384	1	0.01460773	5.50	0.0410
L*T	1	0.00460902	1.73	0.2172	1	0.00399020	1.50	0.2484
L*P	3	0.01263808	1.59	0.2538	3	0.01277818	1.60	0.2499
L*S	1	0.00875622	3.30	0.0995	1	0.00888620	3.34	0.0973
T*P	3	0.00155943	0.20	0.8970	3	0.00154494	0.19	0.8982
T*S	1	0.01436196	5.41	0.0424	1	0.01529874	5.76	0.0373
P*S	3	0.01570711	1.97	0.1824	3	0.01570711	1.97	0.1824

Table B4. ANOVA results for percent of left turns on the yellow arrow for the utilization of signal phases experiment.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	25	0.12543176	0.00501727	2.57	0.0602	0.865544	38.6461
ERROR	10	0.01948484	0.00194848		ROOT MSE		PYA MEAN
CORRECTED TOTAL	35	0.14491660			0.04414163		0.11422016

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
SP	1	0.00037127	0.19	0.6717	1	0.00001653	0.01	0.9242
L	1	0.00700594	3.60	0.0872	1	0.00593082	3.04	0.1116
T	1	0.00004756	0.02	0.8790	1	0.00083183	0.43	0.5262
P	3	0.01643386	2.81	0.0939	3	0.02332529	3.99	0.0416
S	1	0.05009723	25.71	0.0005	1	0.04339509	22.27	0.0008
SP*L	1	0.00045166	0.23	0.6405	1	0.00115929	0.59	0.4583
SP*T	1	0.00003693	0.02	0.8932	1	0.00002380	0.01	0.9142
SP*P	3	0.00837831	1.43	0.2907	3	0.00733195	1.25	0.3417
SP*S	1	0.00055263	0.28	0.6059	1	0.00014792	0.08	0.7865
L*T	1	0.00468809	2.41	0.1519	1	0.00385429	1.98	0.1899
L*P	3	0.00159313	0.27	0.8439	3	0.00074371	0.13	0.9418
L*S	1	0.00355408	1.82	0.2066	1	0.00311647	1.60	0.2347
T*P	3	0.01652512	2.83	0.0928	3	0.01579169	2.70	0.1020
T*S	1	0.00015056	0.08	0.7867	1	0.00003048	0.02	0.9029
P*S	3	0.01554700	2.66	0.1053	3	0.01554700	2.66	0.1053

Table B5. ANOVA results for percent of left turns on the red indication for the utilization of signal phases experiment.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	25	0.16477263	0.00659091	2.77	0.0476	0.873861	56.2828
ERROR	10	0.02378440	0 00237844		ROOT MSE		POR MEAN
CORRECTED TOTAL	35	0.18855703			0.04876925		0.08668113

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
SP	1	0.00070586	0.30	0.5979	1	0.00044162	0.19	0.6757
L	1	0.01284946	5.40	0.0425	1	0.01416537	5.96	0.0348
T	1	0.00184544	0.78	0.3091	1	0.00187744	0.79	0.3952
P	3	0.00332309	0.47	0.7126	3	0.00067601	0.10	0.9611
S	1	0.10250617	43.10	0.0001	1	0.09881251	41.55	0.0001
SP*L	1	0.00111123	0.47	0.5096	1	0.00035234	0.15	0.7084
SP*T	1	0.00246788	1.04	0.3324	1	0.00290296	1.22	0.2951
SP*P	3	0.01682712	2.36	0.1330	3	0.01728472	2.42	0.1265
SP*S	1	0.00027143	0.11	0.7425	1	0.00047991	0.20	0.6629
L*T	1	0.00167350	0.70	0.4212	1	0.00148650	0.62	0.4475
L*P	3	0.00428243	0.60	0.6294	3	0.00385881	0.54	0.6651
L*S	1	0.00674305	2.84	0.1231	1	0.00683000	2.87	0.1210
T*P	3	0.00752388	1.05	0.4109	3	0.00731317	1.02	0.4224
T*S	1	0.00053864	0.23	0.6444	1	0.00058579	0.25	0.6304
P*S	3	0.00210346	0.29	0.8284	3	0.00210346	0.29	0.8284

Table B6. ANOVA results for percent of left turns on green indications for the utilization of signal phases experiment.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	25	0.44029817	0.01781193	5.07	0.0053	0.926934	11.6077
ERROR	10	0 03470873	0.00347087		ROOT MSE		PG MEAN
CORRECTED TOTAL	35	0.47500489			0.05891241		0.50752941

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
SP	1	0.00035370	0.10	0.7561	1	0.00005478	0.02	0.9026
L	1	0.00098456	0.28	0.6059	1	0.00054403	0.16	0.7005
T	1	0.07450774	21.47	0.0009	1	0.07787149	22.44	0.0008
P	3	0.07998601	7.68	0.0059	3	0.05993083	5.76	0.0150
S	1	0.16632882	47.92	0.0001	1	0.15667391	45.14	0.0001
SP*L	1	0.00355481	1.02	0.3354	1	0.00192704	0.56	0.4733
SP*T	1	0.00570790	1.64	0.2286	1	0.00598373	1.72	0.2185
SP*P	3	0.03503892	3.37	0.0631	3	0.04067061	3.91	0.0439
SP*S	1	0.00240163	0.69	0.4249	1	0.00236856	0.68	0.4280
L*T	1	0.01152429	3.32	0.0984	1	0.01035933	2.98	0.1147
L*P	3	0.00452077	0.43	0.7333	3	0.00426337	0.41	0.7497
L*S	1	0.00286941	0.83	0.3846	1	0.00319040	0.92	0.3603
T*P	3	0.05028885	4.83	0.0249	3	0.05006942	4.81	0.0252
T*S	1	0.00023063	0.07	0.8018	1	0.00025723	0.07	0.7910
P*S	3	0.00200013	0.19	0.8994	3	0.00200013	0.19	0.8994

Table B7. ANOVA results for percent of left turns on yellow indications for the utilization of signal phases experiment.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	25	0.19920779	0.00796831	3.34	0.0255	0.892983	11.9683
ERROR	10	0.02387852	0.00238785		ROOT MSE		PY MEAN
CORRECTED TOTAL	35	0.22308631			0.04886565		0.40829196

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
SP	1	0.00092172	0.39	0.5483	1	0.00035995	0.15	0.7060
L	1	0.01724057	7.22	0.0228	1	0.01768208	7.40	0.0216
T	1	0.04621062	19.38	0.0013	1	0.05149872	21.57	0.0009
P	3	0.06564222	9.16	0.0032	3	0.05688193	7.94	0.0053
S	1	0.01022088	4.28	0.0654	1	0.00814829	3.41	0.0945
SP*L	1	0.00157744	0.66	0.4353	1	0.00119518	0.50	0.4954
SP*T	1	0.00144557	0.61	0.4545	1	0.00104118	0.44	0.5240
SP*P	3	0.00808225	1.13	0.3847	3	0.01095521	1.53	0.2666
SP*S	1	0.00045976	0.19	0.6701	1	0.00032293	0.14	0.7207
L*T	1	0.00587422	2.46	0.1476	1	0.00516653	2.17	0.1713
L*P	3	0.00110381	0.15	0.9247	3	0.00182791	0.26	0.8560
L*S	1	0.00036501	0.15	0.7040	1	0.00030187	0.13	0.7296
T*P	3	0.03760264	5.25	0.0197	3	0.03851488	5.38	0.0183
T*S	1	0.00033208	0.14	0.7170	1	0.00031007	0.13	0.7261
P*S	3	0.00214001	0.30	0.8256	3	0.00214001	0.30	0.8256

Table B8. ANOVA results for percent of left turns on ball indications for the utilization of signal phases experiment.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	25	0.64659606	0.02586384	9.91	0.0003	0.961210	8.8480
ERROR	10	0.02609338	0.00260934		ROOT MSE		PR MEAN
CORRECTED TOTAL	35	0.67268945			0.05108188		0.57732692

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
SP	1	0.01310993	5.02	0.0489	1	0.00395958	1.52	0.2462
L	1	0.13859134	53.11	0.0001	1	0.12825659	49.15	0.0001
T	1	0.06527101	25.01	0.0005	1	0.09292417	35.61	0.0001
P	3	0.08882928	11.35	0.0015	3	0.09079611	11.60	0.0014
S	1	0.16995976	65.14	0.0001	1	0.16948833	64.95	0.0001
SP*L	1	0.00455190	1.74	0.2160	1	0.00191683	0.73	0.4115
SP*T	1	0.00162737	0.62	0.4480	1	0.00256309	0.98	0.3450
SP*P	3	0.04322298	5.52	0.0169	3	0.04016209	5.13	0.0210
SP*S	1	0.01410966	5.41	0.0424	1	0.01047060	4.01	0.0730
L*T	1	0.00097892	0.38	0.5539	1	0.00082243	0.32	0.5869
L*P	3	0.01667359	2.13	0.1599	3	0.01633111	2.09	0.1657
L*S	1	0.00149872	0.57	0.4660	1	0.00125394	0.48	0.5040
T*P	3	0.03863298	4.94	0.0235	3	0.03455506	4.41	0.0319
T*S	1	0.00549996	2.11	0.1772	1	0.00714387	2.74	0.1290
P*S	3	0.04403868	5.63	0.0160	3	0.04403866	5.63	0.0160

Table B9. ANOVA results for percent of left turns on arrow indications for the utilization of signal phases experiment.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	25	0.41074798	0.01642992	3.70	0.0178	0.902420	19.6884
ERROR	10	0.04441456	0.00444146		ROOT MSE		PA MEAN
CORRECTED TOTAL	35	0.45516254			0.06664425		0.33849445

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
SP	1	0.01059781	2.39	0.1535	1	0.00263728	0.59	0.4588
L	1	0.07417613	16.70	0.0022	1	0.06177958	13.91	0.0039
T	1	0.03000954	6.76	0.0142	1	0.06388403	14.38	0.0035
P	3	0.10441654	7.84	0.0056	3	0.09281328	6.95	0.0083
S	1	0.01113568	2.51	0.1444	1	0.01125989	2.54	0.1424
SP*L	1	0.00763404	1.72	0.2192	1	0.00282049	0.64	0.4440
SP*T	1	0.00000790	0.00	0.9672	1	0.00003069	0.01	0.9354
SP*P	3	0.02777951	2.08	0.1659	3	0.01940536	1.46	0.2846
SP*S	1	0.02141788	4.82	0.0528	1	0.01769556	3.98	0.0739
L*T	1	0.00000034	0.00	0.9932	1	0.00000118	0.00	0.9873
L*P	3	0.02144235	1.61	0.2486	3	0.01890430	1.42	0.2944
L*S	1	0.00115320	0.26	0.6214	1	0.00147774	0.33	0.5768
T*P	3	0.02192063	1.65	0.2409	3	0.01847195	1.39	0.3031
T*S	1	0.01157153	2.61	0.1378	1	0.01396352	3.14	0.1066
P*S	3	0.05848491	4.39	0.0324	3	0.05848491	4.39	0.0324

Table B10. ANOVA results for percent of left turns on the last yellow indication before the red indication for the utilization of signal phases experiment.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	25	0.55938246	0.02237530	5.93	0.0028	0.936809	34.4544
ERROR	10	0.03773234	0.00377323		ROOT MSE		PEC MEAN
CORRECTED TOTAL	35	0.59711480			0.06142666		0.17828384

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
SP	1	0.00335927	0.89	0.3676	1	0.00141172	0.37	0.5644
L	1	0.02063733	5.47	0.0414	1	0.01904666	5.05	0.0484
T	1	0.01354868	3.59	0.0874	1	0.01004254	2.66	0.1339
P	3	0.07142840	6.31	0.0113	3	0.05468183	4.83	0.0249
S	1	0.33614706	89.09	0.0001	1	0.31930628	84.62	0.0001
SP*L	1	0.00000058	0.00	0.9903	1	0.00050000	0.13	0.7234
SP*T	1	0.00052313	0.14	0.7174	1	0.00042303	0.11	0.7447
SP*P	3	0.00537467	0.47	0.7067	3	0.00624094	0.55	0.6587
SP*S	1	0.00199221	0.53	0.4841	1	0.00056524	0.15	0.7068
L*T	1	0.00074892	0.20	0.6654	1	0.00084474	0.22	0.6463
L*P	3	0.00107707	0.10	0.9610	3	0.00078979	0.07	0.9748
L*S	1	0.02608324	6.91	0.0252	1	0.02335198	6.19	0.0321
T*P	3	0.02595420	2.29	0.1402	3	0.02235618	1.98	0.1817
T*S	1	0.00562886	1.49	0.2500	1	0.00687020	1.82	0.2068
P*S	3	0.04687884	4.14	0.0378	3	0.04687884	4.14	0.0378

Table B11. ANOVA results for percent of left turns on the last yellow indication before the red indication plus the red indication for the utilization of signal phases experiment.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	25	1.09164530	0.04366561	6.10	0.0025	0.936416	31.9439
ERROR	10	0.07163933	0.00716393		ROOT MSE		PECOR MEAN
CORRECTED TOTAL	35	1.16328463			0.08464002		0.26496497

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
SP	1	0.00098541	0.14	0.7185	1	0.00027417	0.04	0.8468
L	1	0.00091618	0.13	0.7278	1	0.00036067	0.05	0.8270
T	1	0.02539474	3.54	0.0801	1	0.02060426	2.88	0.1208
P	3	0.10021862	4.66	0.0275	3	0.06142232	2.86	0.0907
S	1	0.80990597	113.05	0.0001	1	0.77337337	107.95	0.0001
SP*L	1	0.00116276	0.16	0.6955	1	0.00001269	0.00	0.9670
SP*T	1	0.00526346	0.73	0.4114	1	0.00554232	0.77	0.3997
SP*P	3	0.01563364	0.73	0.5586	3	0.01385708	0.64	0.6037
SP*S	1	0.00373434	0.52	0.4866	1	0.00206681	0.29	0.6012
L*T	1	0.00018339	0.03	0.8761	1	0.00009007	0.01	0.9129
L*P	3	0.00940664	0.44	0.7310	3	0.00526243	0.24	0.8631
L*S	1	0.00630229	0.88	0.3704	1	0.00492373	0.69	0.4264
T*P	3	0.03589730	1.67	0.2357	3	0.03144313	1.46	0.2829
T*S	1	0.00964999	1.35	0.2728	1	0.01147587	1.60	0.2343
P*S	3	0.06698858	3.12	0.0751	3	0.06698858	3.12	0.0751

Table B12. Mean values of the percent of left turns on the green ball for the utilization of signal phases experiment.

Factor	Level	Number of observations	Mean percent of left turns on green ball	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
SP	30	18	29.4	50
	50	18	27.2	30
L	140	18	31.1	----
	230	18	25.6	----
T	600	18	36.1	----
	1000	18	20.6	----
P	none	9	32.8	one perfect, early
	one perfect	9	28.3	none, early
	two perfect	9	18.6	----
	early	9	33.5	none, one perfect
S	perm.-pro.	18	33.4	----
	pro.-perm.	18	23.3	----

Table B13. Mean values of the percent of left turns on the yellow ball for the utilization of signal phases experiment.

Factor	Level	Number of observations	Mean percent of left turns on yellow ball	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
SP	30	18	28.6	50
	50	18	30.2	30
L	140	18	33.1	----
	230	18	25.8	----
T	600	18	25.9	----
	1000	18	32.9	----
P	none	9	21.0	----
	one perfect	9	29.7	two perfect, early
	two perfect	9	34.2	one perfect, early
	early	9	32.8	one perfect, two perfect
S	perm.-pro.	18	31.0	----
	pro.-perm.	18	27.8	----

Table B14. Mean values of the percent of left turns on the green arrow for the utilization of signal phases experiment.

Factor	Level	Number of observations	Mean percent of left turns on green arrow	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
SP	30	18	21.0	50
	50	18	23.8	30
L	140	18	19.1	----
	230	18	25.7	----
T	600	18	19.3	----
	1000	18	25.6	----
P	none	9	23.7	one perfect, two perfect
	one perfect	9	24.1	none,two perfect
	two perfect	9	25.8	none, one perfect
	early	9	16.1	----
S	perm.-pro.	18	24.6	----
	pro.-perm.	18	20.3	----

Table B15. Mean values of percent of left turns on the yellow arrow for the utilization of signal phases experiment.

Factor	Level	Number of observa-tions	Mean percent of left turns on yellow arrow	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
SP	30	18	11.1	50
	50	18	11.7	30
L	140	18	10.0	230
	230	18	12.8	140
T	600	18	11.3	1000
	1000	18	11.5	600
P	none	9	14.5	one perfect, two perfect, early
	one perfect	9	10.4	none,two perfect, early
	two perfect	9	12.4	none, one perfect, early
	early	9	8.4	none, one perfect, two perfect
S	perm.-pro.	18	7.8	----
	pro.-perm.	18	15.0	----

Table B16. Mean values of percent of left turns on the red indication for the utilization of signal phases experiment.

Factor	Level	Number of observa-tions	Mean percent of left turns on red	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
SP	30	18	8.2	50
	50	18	9.1	30
L	140	18	6.7	----
	230	18	10.6	----
T	600	18	8.0	1000
	1000	18	9.4	600
P	none	9	8.0	one perfect, two perfect, early
	one perfect	9	7.4	none,two perfect, early
	two perfect	9	10.0	none, one perfect, early
	early	9	9.3	none, one perfect, two perfect
S	perm.-pro.	18	3.3	----
	pro.-perm.	18	14.1	----

Table B17. Mean values of percent of left turns on green indications for the utilization of signal phases experiment.

Factor	Level	Number of observa-tions	Mean percent of left turns on green indications	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
SP	30	18	50.4	50
	50	18	51.1	30
L	140	18	50.2	230
	230	18	51.3	140
T	600	18	55.3	----
	1000	18	46.2	----
P	none	9	56.5	one perfect, early
	one perfect	9	52.5	none, early
	two perfect	9	44.4	early
	early	9	49.6	none, one perfect, two perfect
S	perm.-pro.	18	57.9	----
	pro.-perm.	18	43.6	----

Table B18. Mean values of percent of left turns on yellow indications for the utilization of signal phases experiment.

Factor	Level	Number of observa-tions	Mean percent of left turns on yellow indications	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
SP	30	18	41.3	50
	50	18	40.3	30
L	140	18	43.1	----
	230	18	38.6	----
T	600	18	37.2	----
	1000	18	44.4	----
P	none	9	35.5	one perfect, early
	one perfect	9	40.1	none, early
	two perfect	9	46.6	----
	early	9	41.1	none, one perfect
S	perm.-pro.	18	38.8	----
	pro.-perm.	18	42.8	----

Table B19. Mean values of the percent of left turns on ball indications for the utilization of signal phases experiment.

Factor	Level	Number of observa-tions	Mean percent of left turns on ball indications	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
SP	30	18	59.6	----
	50	18	55.8	----
L	140	18	64.1	----
	230	18	51.3	----
T	600	18	62.0	----
	1000	18	53.5	----
P	none	9	53.8	one perfect, two perfect
	one perfect	9	58.0	none, two early
	two perfect	9	52.8	none, one perfect
	early	9	66.3	----
S	perm.-pro.	18	64.4	----
	pro.-perm.	18	51.1	----

Table B20. Mean values of percent of left turns on arrow indications for the utilization of signal phases experiment.

Factor	Level	Number of observations	Mean percent of left turns on arrow indications	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
SP	30	18	32.1	50
	50	18	35.6	30
L	140	18	29.1	----
	230	18	38.6	----
T	600	18	30.6	----
	1000	18	37.1	----
P	none	9	38.1	one perfect, two perfect
	one perfect	9	34.6	none, two early
	two perfect	9	38.2	none, one perfect
	early	9	24.4	----
S	perm.-pro.	18	32.4	protected-permissive
	pro.-perm.	18	35.3	permissive-protected

Table B21. Mean values of the percent of left turns on the last yellow indication before the red indication for the utilization of signal phases experiment.

Factor	Level	Number of observa-tions	Mean percent of left turns on last yellow before red	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
SP	30	18	18.8	50
	50	18	16.9	30
L	140	18	20.3	----
	230	18	15.3	----
T	600	18	15.9	1000
	1000	18	19.8	600
P	none	9	10.7	----
	one perfect	9	17.8	two perfect, early
	two perfect	9	22.4	one perfect, early
	early	9	20.4	one perfect, two perfect
S	perm.-pro.	18	7.8	----
	pro.-perm.	18	27.8	----

Table B22. Mean values of percent of left turns on the last yellow indication before the red indication plus the red indication for the utilization of signal phases experiment.

Factor	Level	Number of observations	Mean percent of left turns on last yellow plus red	Levels of same factor which were not significantly different at 0.05 level using Student-Newman-Keuls test
SP	30	18	27.0	50
	50	18	26.0	30
L	140	18	27.1	230
	230	18	25.9	140
T	600	18	23.8	1000
	1000	18	29.2	600
P	none	9	18.8	one perfect, early
	one perfect	9	25.2	none, two perfect, early
	two perfect	9	32.4	one perfect, early
	early	9	29.6	none, one perfect, two perfect
S	perm.-pro.	18	11.1	----
	pro.-perm.	18	41.9	----

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